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Accumulation and recovery of nitrogen in mixed farming systems using legumes and other fertility building crops

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ACCUMULATION AND RECOVERY OF NITROGEN IN MIXED FARMING SYSTEMS USING LEGUMES AND OTHER FERTILITY-BUILDING CROPS

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DECLARATION

I declare that this project is a result of my own work and except where stated and referenced otherwise, all the written work and investigations are my own. This work has not been accepted or submitted for any comparable academic award elsewhere.

Joanna May Doel

Abstract

Fertility-building crops (FBCs) offer the opportunity to alleviate the costs of inorganic fertiliser by providing an alternative supply of available nitrogen (N) in soils. A survey of relevant literature reviewed the types of FBCs, their nitrogen accumulation potentials, residue characteristics, and subsequent release patterns. It also identified a paucity of data concerning the response of different species to UK climatic, soil, and management conditions. In order to investigate these relationships further pot and field trials were established in 2007 at the Royal Agricultural College, Cirencester (SP 00481 01382) and at Coates Manor Farm (SO 98473 00402) on Sherborne series (typical Cotswold) soils, to investigate the biology and morphology of FBCs potentially suitable for short term fertility-building, their accumulation of N under field conditions, and its subsequent recovery within test crops. Data so obtained was used as a verification and refinement tool for the FBC model (Cuttle *et al*, 2003), a simple, commercially applicable, rotation-based model which can be applied to both organic and conventional production systems.

Nine leguminous and two non-leguminous FBC treatments were established in April 2007 by straight sowing, followed by mulching at the conclusion of the nitrogen accumulation phase and by undersowing in spring barley (*Hordeum sativum*). The recovery test crops (winter and spring wheat *Triticum aestivum* L.) were established in September 2007 and March 2008.

All FBCs established successfully. Above-ground dry matter (DM) yield and residue quality (C:N ratio) of FBCs varied significantly ($P<0.05$) between crops and cropping regimes with a significant correlation ($r^2=0.418$) between DM yields and C:N ratios. FBCs and cropping regimes had significant effects ($P<0.001$ and $P<0.05$ respectively) on potential mineralisable nitrogen (PMN) levels in the soil and on the grain yields of winter and spring wheat test crops.

Straight sown *Lupinus albus*, *Trifolium pratense*, *Trifolium repens* and a legume mixture resulted in higher winter wheat grain yields. However, the opportunity cost

associated with straight sowing (i.e. the gross margin foregone from a spring barley crop) meant that the rotation would probably not be viable economically. Undersown *Medicago lupulina*, *Vicia villosa*, *T. pratense*, *T. repens* and the legume mixture gave worthwhile yield increases in spring wheat without incurring a yield penalty in the spring barley cover crop.

Following enhancement and using actual data from the trials, the FBC model (Cuttle *et al*, 2003) provided encouraging predictions ($R>0.6$) for soil mineral nitrogen (SMN) and key parameters were identified for future use.

It was concluded that FBCs established for short term soil fertility building could provide a worthwhile enhancement of soil N levels and grain yields in a conventional arable rotation, particularly in spring wheat following FBCs undersown in spring barley. It was also concluded that the FBC model (Cuttle *et al*, 2003), following further enhancement, and using additional data from these and other similar trials, could provide reasonably accurate estimates of SMN to aid more precise applications of N fertiliser in the future.

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Abbreviations

Abbreviation	Description
ADAS	Agricultural Development Advisory Service
Al	Aluminium
ANOVA	Analysis of Variance Analysis
B	Boron
BCPC	British Crop Production Council
BNF	Biological nitrogen fixation
C	Carbon
CH_4	Methane
Cu	Copper
CNS	Carbon/Nitrogen/Sulphur
C1	Certification1
DEFRA	Department for Environment, Food and Rural Affairs
DM	Dry Matter
EC	European Community
EEC	European Economic Community
EU	European Union
EUROPA	European Union
FAO	Food & Agriculture Organisation
FBCs	fertility building crops
Fe	Iron
FW	Fresh Weight
FWI	Farmers Weekly Interactive
FYM	Farm Yard Manure
GAI	Green leaf Area Index
GS	Growth Stage
HDRA	Henry Doubleday Research Association

HGCA	Home Grown Cereal Association
IPPC	Integrated Pollution and Prevention Control
ISTA	International Seed Test Association
K	Potassium
L	Lignin
MIT	Mineralisation Immobilisation Turnover
Mn	Manganese
MTR	Mid Term Review
N	Nitrogen
NH_3	Ammonia
NH_4	Ammonium
NO_3	Nitrate
NO_x	Nitrogen Oxide
NUE	Nitrogen use Efficiency
N_2O	Nitrous Oxide
OECD	Organisation for Economic Co-Operation and Development
P	Phosphorus
P/L/N	Polyphenol/Lignin/Nitrogen
PMN	Potential Mineralisable Nitrogen
SFP	Single Farm Payment
Si	Silicon
SMB	Soil Microbial Biomass
SMN	Soil Mineral Nitrogen
SMR	Soil Microbial Residue
SNS	Soil Nitrogen Supply
SOC	Soil Organic Carbon
SOM	Soil Organic Matter

SON	Soil Organic Nitrogen
SW	Spring Wheat
R	Statistical coloration
WFD	Water Framework Directive
WHC	Water Holding Capacity
WW	Winter Wheat
Zn	Zinc
%Ndfa	% Nitrogen derived from the atmosphere

Chapter 1. Introduction

The global population in 2011 was 7.0 billion (United Nations, Department of Economics and Social Affairs, 2011), which is projected to increase to around 9 billion by 2050 (Commission on Sustainable Agriculture and Climate Change, 2012). Population expansion continues to pressurise food production systems (Commission on Sustainable Agriculture and Climate Change, 2012), with an estimated 925 million people undernourished in October 2010 worldwide (Food & Agriculture Organisation (FAO), 2012; Commission on Sustainable Agriculture and Climate Change, 2012). Fertiliser plays a fundamental role in sustaining food supplies, and it is estimated that 48% of the world's dietary protein originates from the Haber-Bosch technique (Erisman *et al.,* 2008). Usage of fertiliser Nitrogen (N) increased worldwide from 106-119 kg ha^{-1} over the 2002-2008 period (FAO, 2012). Inorganic nutrient sources have been used as a tool to sustain food supply as levels of productive arable land available per person have reduced by more than half over a 50 year period (FAO, 2012). Population growth coupled with changes in dietary patterns, particularly in developing countries has further exacerbated reliance on fertilisers (FAO, 2008). This is as a consequence of economic growth and urbanisation, providing greater "freedom" of food choice and preference, a move towards more nutrient demanding, greenhouse gas emitting systems, and larger areas of land required per unit of output for products such as meat, dairy and processed foods (Commission on Sustainable Agriculture and Climate Change, 2012; FAO, 2012) .

Nitrogen acquisition and assimilation is second only to photosynthesis in terms of importance for plant growth and development and is perhaps the single most limiting factor to crop yield (St. Luce *et al.,* 2011; Lobell, 2007; Vance, 1997). Other key factors include the incidence of weeds, pests and diseases, the availability of phosphorus and potassium, soil of a suitable pH and adequate water supply (Cuttle *et al.,* 2003; Cherr *et al.,* 2006; Brainard *et al.,* 2011). Within developed countries crop grain yields significantly increased between 1950 and 1990, much of this attributed to the Green Revolution, exploiting crop genetics, crop nutrition and protection (Waggoner, 1994; Herder, 2010). Fertiliser levels within total crop N inputs rose over a similar period (1950-1996) from 7% to 43% (Mosier, 2001), mainly due to mineralisation of organic N rarely being sufficient to achieve modern cultivar yield ceilings (St. Luce *et al.,* 2011).

Cereal production is substantially influenced by N supply (Zebarth *et al.,* 2009) and is a major source of human nutrition (Hardarson and Atkins, 2003), representing 50% of the global calorific intake (FAO, 2012) with demand predicted to increase by 70% over current levels by 2050 (Commission on Sustainable Agriculture and Climate Change, 2012). Cereals are a fundamental component of European agriculture, producing on average 278.8M t (est. 2010) (FAO, 2010) with wheat (*Triticum aestivum* L.) varieties in 2008 representing 150.5M t (FAO, 2010). Cereal cultivation in many areas has contributed to the deterioration of soil quality causing sustainability and environmental concerns (Hardarson and Atkins, 2003), potentially contributing to the 12 million ha annually which are lost to degradation (FAO, 2012; Commission on Sustainable Agriculture and Climate Change, 2012). Grain prices continue to fluctuate and figure 1.1 illustrates the situation reference US "soft red winter wheat" during the period 2006 – 2011, also reflected in UK price fluctuations. Such variation illustrates the potential for UK exposure to world market volatility and sustains the pressure for economic efficiency within the arable sector, especially in light of apparent yield ceilings (IFA, 2003).

Figure 1.1 Price fluctuations of US soft red winter wheat

Mongabay (2012a)

Nitrogenous fertiliser is a critical cost component and currently represents about 56% of the variable costs of cereal production (Readman, 2012). UK price increases are a reflection of inelastic supply and substantial demand (Farmers Weekly Interactive (FWI), 2005). Price increases in excess of 50% occurred over the period 2001-2006 (Home Grown Cereal Association (HGCA). 2006) and peaked in January 2009 at £390/t for 34.5%N ammonium nitrate (FWI, 2009). Fluctuations in the price of Eastern European bulk urea over a similar period are illustrated in figure 1.2.

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Figure 1.2 Price fluctuations of Eastern European bulk urea

Mongabay (2012b)

N fertiliser supply levels in the short term may appear to be contracting, largely due to tight market conditions in Asia, Latin America and North America, and market stagnation in Europe with expected growth at just 1.4% and 0.06% respectively per annum (2007-2012 period) (FAO, 2008). Contrary to this, developing countries in particular in Asia, account for 69% of the projected growth in global demand (FAO, 2008). As traditional agricultural requirements compete with emerging agricultural markets and expanding biofuel production, the price of fertiliser will probably continue to escalate.

World market economics, as well as international policy, are questioning the viability of the utilisation of inorganic N sources, and, in an increasingly environmentally aware society, agricultural accountability for environmental degradation has risen on the political agenda (Landcare, 2004; Herder *et al.,* 2010; Espinoza *et al.,* 2012).

The N cycle involves complex interactions (St. Luce *et al,* 2011). Human activities have induced the global N fluxes of biologically active N (Ammonia

($NH_{3)}$, Ammonium ($NH_{4)}$, Nitrate ($NO_{3)}$, Nitrogen Oxide ($NO_{x)}$, Nitrous Oxide (N_2O)) to double (Vitousek *et al.,* 1997). Natural N additions to agricultural systems account for 30-50% of the total N added to agricultural land (Herridge *et al.,* 2008) and primarily result from biological nitrogen fixation (BNF) and therefore co-occur with carbon C fixation (Tonitto *et al.,* 2006). Agriculture in the form of inorganic fertiliser accounts for 80 Tg N yr^{-1} out of 170 Tg N yr^{-1} of reactive N introduced to agro-ecosystems annually (Smil, 1999). The addition of simple molecules from fertiliser applications, the simplification of rotations, chemical weed control and the adoption of bare fallows interfere with natural nutrient cycling (Auclair, 1976; Mitsch *et al.,* 2001; Dampney *et al*., 2002). Pretty *et al.,* (2000), estimated the total costs of UK agricultural activities to amount to £2343m (1996) of which 16m was attributable to nitrate, and 55m to phosphate pollution and soil degradation.

The decoupling of the C and N cycles is a defining trait of agro-ecosystems by crop residue removal off site and the introduction of synthetic readily available nutrient sources (Woodmansee, 1984). This disengagement of energy flows and nutrient cycles may lead to severe and widespread consequences (Drinkwater, 2004) such as reductions in soil stability / degradation, decreasing species biodiversity, increased soil erosion, ozone depletion and the associated cost implications of diffuse pollution to the water supply industry, farmers and even tourism (Laegreid *et al.,* 1999; Haygarth *et al*., 2003; Department for Environment, Food and Rural Affairs (DEFRA), 2003a; DEFRA, 2003b; DEFRA. 2004c; DEFRA, 2011 World Resources Institute, 2005; Neumann *et al.,* 2012).

European legislation has attempted to mediate these negative impacts via the 1980 European Community (EC) Directive and the 1991 EC Nitrate Directive. (91/676/European Economic Community (EEC)) (DEFRA, 2003b; European Union (EUROPA). 2003; Readman *et al*., 2002). However, these were remote from producer based legislation. Policy post Mid Term Review (MTR) has taken a more integrated approach e.g. Integrated Pollution and Prevention Control (IPPC) 1996, the European Union (EU) Water Framework Directive (WFD) (2000/60/EC), the soil framework directive (COM (2006) 232) and

Thematic Strategy for Soil Protection (COM (2012)46) enforced by schemes such as the Soil Protection Review, Good Agricultural and Environmental Conditions and Nitrate Vulnerable Zones under the cross-compliance aspect of the Single Farm Payment (SFP) (European Commission, 2012; DEFRA, 2004e; DEFRA, 2005; Ingram and Morris, 2007). Future policy such as the draft water bill (July 2012) may be informed by papers such as the DEFRA white paper – Water for Life (December 2011) (DEFRA, 2011; DEFRA, 2012).

Political pressure is being exerted as a result of the perceived negative effects of fertiliser utilisation since global N recovery to biomass averages just 45-55% (Smil, 1999; Gallaway and Cowling, 2002; Lobell, 2007). However it should be remembered that considerable quantities of N and P in water is derived from urban and domestic sources (DEFRA, 2009). Global annual energy requirement for fertiliser production is approximately 1.1% (Dawson and Hilton, 2011), natural gas reforming via steam ammonia plant methane (CH_4) is currently the most energy efficient production systems for NH_3 production and accounts for 70% of worldwide production (Pach, 2007; Dawson and Hilton, 2011). Tonitto *et al.,* (2006), Lobell (2007) and Dawson and Hilton (2011) suggested that inefficiency in N fertiliser usage is a problem that must be addressed significantly to reduce the anthropogenic forcing of the global N cycle. Ecological and environmental concerns over the increased use of chemical fertiliser are driving further a re-examination of their usage (Ayoub, 1999; Fageria, 2002; Herder *et al.,* 2010).

The viable options commercially are to strive for higher nitrogen use efficiency (NUE) from inorganic inputs, by tailoring inputs to improve synchronicity between plant available N and crop uptake (Ma *et al.,* 1999; Zebarth and Rosen, 2007; Sharifi *et al.,* 2007; Herder *et al.,* 2010). The use of more organic nutrient sources could also be a viable option (Clement *et al*., 1998). Organic nutrient sources, including livestock or crop residues, can provide producers with the opportunity to re-couple the C and N cycles (Tonitto *et al.,* 2006) to influence physical parameters, restore eroded soils and soil productivity and replace some mineral fertiliser inputs (Clement *et al*., 1998; Larney and Jansen. 1996; Fageria and Baligar. 2005; Koné *et al.,* 2008;

Okpara *et al.,* 2005; Chirinda *et al.,* 2010). Dawson and Hilton (2011) considered the global requirement for N fertiliser production and use and concluded that the widespread “extensification” of cereal production involving main crop legume culture would be unrealistic because of the opportunity costs involved. However, it was still important to identify and maximise the efficiency of re-use of N residues where possible, thus optimising NUE and aiding the economic and environmental accountability of future crop production (Elfstrand *et al.,* 2007). It is in this context that the results of this detailed study of the use of short term fertility-building crops (FBCs) should be considered.

1.1 Research and resulting thesis aims

The aim of this research is to consider the attributes of a range of FBCs and to measure, as accurately as possible, their contributions as sources of N for subsequent cropping and their effects on subsequent crop yields.

The null hypothesis is that fertility building crops have no influence on the accumulation of nitrogen and its recovery in the following season’s cropping and have no effect on subsequent crop yields.

Chapter 2 details a review of the literature concerning FBCs, their N accumulation potentials, residue characteristics, and subsequent release patterns.

Chapter 3 contains an account of a small scale pot experiment designed to establish the characteristics and suitability of selected FBCs, their actual N accumulation and residue quality when grown as single plants, in pots, in soil taken from the experimental area.

Chapter 4 describes an account of a large scale field trial designed to investigate the N contributions of a range of short term FBCs and establishment methods on the accumulation of N and its recovery in subsequent winter and spring wheat crops.

Chapter 5 contains an account of the use and further development of the FBC model (Cuttle *et al.,* 2003) using information derived from the above investigations.

Chapter 6 brings together all strands of the investigation to evaluate them and to draw conclusions.

Chapter 2 Fertility building crops (FBCs) as nutrient sources and the concept of "Green Manuring"

The use of FBCs as nutrient sources or soil improvers is an ancient concept (Fageria, 2007; Allison, 1973; Espinoza *et al.,* 2012), utilised by the Greeks around 300BC and by the early Romans who found benefits from growing *Faba* beans (*Vicia faba* L.) and lupins (*Lupinus* spp.). Such practices also extended across India and China (Fageria, 2007) and were fundamental to early agriculture since soil productivity was dependent on natural resources and a sound ecological equilibrium between soil, plant, animal and human (Fageria, 2007). A decline in their use can be associated with agricultural intensification and the increased use of fertilisers and agro-chemicals (Espinoza *et al.,* 2012).

Organic amendments whether in the form of manures, crop residues or diversified crop rotations offer the opportunity to provide nutrient sources for subsequent plant growth. Thorup-kristensen *et al.,* (2003; 2012); Brainard *et al.,* (2011); Peoples *et al.,* (1995); Hendrix *et al.,* (1992); Yadvinder–Singh *et al.,* (1992); LaRue and Patterson, (1981) have discussed the potential for leguminous FBCs as "green manures" as a means to replace or to reduce inorganic N usage. Also they re-integrate the C and N cycles, acting as sources of energy via organic C for heterotrophic soil microorganisms (Elfstrand *et al.,* 2007) ultimately influencing soil characteristics, including soil aggregation, structure and hydraulic conductivity and water availability (Brainard *et al.,* 2011; Allison, 1973; Faris, 1986; Elliot and Papendick, 1986; Chirinda *et al.,* 2010; Brandsæter *et al.,* 2012). The culmination of organic amendments on biological and chemical soil properties and nutrient accumulation potential should equate to improvements in soil organic matter (SOM), higher N mineralisation potential, reduced nitrate leaching (Drinkwater *et al.,* 1998; Sanchez *et al.,* 2001; Constantin *et al.,* 2010; Chirinda *et al.,* 2010; Zotarelli *et al.,* 2012; Brandsæter *et al.,* 2012) and ultimately, improved crop yields (Faris, 1986; Elliot and Papendick, 1986; Bergkvist *et al.,* 2011; Espinoza *et al.,* 2012).

FBCs are crops grown within a rotation and specifically designed to improve nutrition for a following crop. The length of the fertility accumulation phase often dictates the term used to describe them. Titles given to FBCs (listed from shortest to longest accumulation phases) include, catch crops, cover crops, green manures and leys (further FBCs terminology characteristics discussed in this section and 2.2.1). In this thesis the term fertility-building crops or FBCs will normally be used to describe all of these except where a specific reference is indicated by the original source.

“Green manures” are defined by the Soil Science Society of America (1997) as “plant material incorporated into the soil while green or at maturity for soil improvement” and by (Meelu *et al.,* 1994) as “green plant material, which is grown in situ or cut and imported for incorporation into the soil to improve its productivity”. They can take many forms, including the standard method of returning a green crop directly to the soil. Such crops can be totally incorporated at the conclusion of the growth period, or by a staggered cutting regime, often referred to as mulching. Mulching is “multiple chops” of vegetation where material is left on the surface soil horizon and modified by soil macrofauna (Stopes *et al.,* 1996). Green leaf manuring, a process of importing material to trees or shrubs (Singh *et al*., 1991) and the green fallow system whereby a green cover crop replaces a bare fallow in a wheat/fallow system, have also been adopted, principally in the USA (Pikul *et al*., 1997). Another form is the practice of living mulch, which is a form of intercropping, where the crop is maintained rather than killed off and a cash crop is established (Nakamoto and Tsukamoto, 2006; Kosinski *et al.,* 2011). Living mulch can derive the same soil health and crop nutritional benefits as the other green manuring practices with the additional benefits of reduction in weed and disease pressures (Kosinski *et al.,* 2011; Hiltbrunner *et al.,* 2007).

Cover crops or catch crops are crops inserted into a cropping window between two main cash crops, overwintered in Northern Europe (Thorup-Kristensen *et al.,* 2012) or summer fallows in North Carolina (Brainard *et al.,* 2011). Short fertility building phrases allow a higher inclusion level within the rotation, whilst reducing the opportunity costs from not establishing a cash crop (Thorup – Kristensen *et al.,* 2012; Flower *et al.,* 2012). Post summer harvest there is usually sufficient temperature and light for some crop growth (Thorup-Kristensen *et al.,* 2003; Bergkvist *et al.,* 2011) and these circumstances are also conducive to nutrient mineralisation. Cover crops therefore can increase the retention of post-harvest surplus inorganic soil N (McCracken *et al.,* 1994; Drinkwater and Snapp, 2005; Bergkvist *et al.,* 2011). Establishment of a cover crop over the winter period can also be a useful environmental tool as high precipitation, high percolation and low evaporation rates leave soil predisposed to leaching nutrients (Thorup-Kristensen *et al.,* 2003) and therefore acting as a useful N management tool (Thorup – Kristensen *et al.,* 2012). Cover crops have been successfully implemented in extensive systems. Examples include Northern European cash grain rotations, Australian arid region wheat / hay rotations and African low input grain systems (Thorup-kristensen *et al.,* 2003; 2012: Drinkwater and Snapp, 2005) and are currently recommended for many EU and UK agri-environmental schemes (Constantin *et al.,* 2010).

Green manure, cover or catch crops usually refer to crops grown over a relatively short period of just a few months. Ley farming has traditionally involved the growing of perennial legume or legume / grass mixtures for longer periods within a mixed farming rotation and reached a peak of popularity during the 1950s and 1960s (Wilkins 2000). This thesis, however, concentrates on the use of FBCs over a short time period of less than 12 months. Thorup – Kristensen *et al.,* (2012) Tanaka *et al.*, (2002) and Fychan *et al.,* (2006) all concluded that the integration of FBCs into a dynamic cropping system, can be economically viable, environmentally sustainable and socially acceptable.

2.1 Types of FBCs

FBCs are usually split into two predominant categories, “N fixers” and “N holders”. (Cuttle *et al*., 2003) “N fixers” are leguminous crops that are able to generate their own N. “N holders” (also commonly referred to as “N lifters”) are non-legume crops able efficiently to harvest and hold N from the soil profile.

2.1.1 N fixers (legumes)

The ability of leguminous plants to obtain N from a source other than mineral N was demonstrated by Boussingault in the 19th Century (Amarger, 2001). The legume family consists of 16-19,000 species (Allen and Allen, 1981) and only 10-15% have been checked for nodulation and N fixation capacity, and only approximately 1% - mostly contained in the sub-family *Papilionoideae* - are of agricultural importance (Amarger, 2001). The main genera of agricultural interest are *Trifolium*; *Lotus*; *Onobrychis*; *Ornithopus*; *Vicia*; *Hedysarum* and *Pisum* (Frame, 2005). Legume diversity is such that it traverses all sectors of agriculture from arable cash crops and ensilable forage to marginally tolerant pasture plants. This is the only group to provoke the formation of nodules, which are benign plant galls on the roots or stems of host plants (Frame, 2005; Hardarson and Atkins, 2003). Temperate legumes usually nodulate in the root zone.

Leguminous plants are the major source of N inputs into the biosphere (Hardarson and Atkins, 2003; Meelu *et al.,* 1994; Herder *et al.,* 2010). *Rhizobium* symbiosis N contributions to agricultural land varies, however, estimates are in the range of 30-50% of the worldwide (Vance. 1997; Herridge et al., 2008; Herder et al., 2010). Appropriate well managed use of BNF may reduce inorganic N requirements and N losses (Drinkwater *et al.,* 1998; Drinkwater and Snapp, 2005; Espinoza *et al.*, 2012). Legume fixation is the mainstay of fertility-building within “organic” and other sustainable systems but also possesses the ability to transcend into conventional agriculture (Vance. 1997; DEFRA. 2003).

The bacteria involved in BNF are collectively known as *Rhizobia* (genera *Rhizobium*; *Allorhizobium*; *Mesorhizobium*; *Sinorhizorbium*; *Bradyrhizobium* and *Azorhizobium*) (Frame, 2005; Gage, 2004; Hardarson and Atkins, 2003; Herder *et al.,* 2010). These can exist as free-living organisms within soil or in the nodule cells of legumes as nitrogen–fixing symbionts (Gage, 2004).

Fixation of N (diazotrophy) is not restricted to this group of bacteria, but it is only this symbiotic relationship which induces, via infection, the formation of benign plant galls or nodules (Amarger, 2001; Hardarson and Atkins, 2003; Herder *et al.,* 2010). Allen and Allen (1981) identified *Rhizobium, Bradyrhizobium* and *Azorhizobium* as the most significant symbionts in agriculture with potential fixation levels of between 10-350kg N ha^{-1} $season^{-1}$. *Rhizobium /* host relationships are species or group specific ranging from narrow to a very large number of species, usually from the same taxon and exhibiting similar nodulation and physiological characteristics (Amarger, 2001; Broughton *et al.,* 2000; Day *et al.,* 2000; Graham and Vance, 2000; Pacios Bras *et al.,* 2000; Perret *et al.,* 2000). However, infection from native soil *Rhizobium* strains can take place and result in inefficient or ineffective nodule formation (Meelu *et al.,* 1994). Examples of the selectivity of *Rhizobium* species to legume hosts are: lucerne (*Melilotus sativa*) and other *Melilotus* genera which require *Sinorhizobium meliloti*; clovers (*Trifolium*) which require *Rhizobium leguminosarium* bv. *Trifolii* and birdsfoot trefoil (*Lotus corniculatus* L.) which requires *Mesorhizobium loti* (Amarger, 2001).

Rhizobia in the field have a very diverse native population as a result of natural distribution and not all symbiotic relationships induce N fixation (Amarger 2001). Formation of effective nodules is dependent on plant, soil and climatic factors and their interactions (Fageria. 2007; Espinoza *et al.,* 2012). Efficacy of nodulation in plants is a reflection of unique developmental steps early in seedling life, but multiple factors at this key timing such as drought, waterlogging, low soil fertility, including N (Ma *et al.,* 1998) and P (Zapata and Baert, 1989), unfavourable pH and temperature (Giller and Wilson, 1991), as well as tillage and establishment management (Zotarelli *et al.,* 2012) will potentially alter the pattern, frequency and ultimately levels of N fixation (Hardarson and Atkins, 2003; Chalk *et al.,* 2010; Espinoza *et al.,* 2012). Species and cultivars well adapted to the indigenous climate will take optimal advantage of the native *Rhizobium* population and induce high fixation potentials (Hardarson *et al.,* 1994). Alternatively, to mediate ineffective nodulation and the introduction of non-native species, inoculants are often introduced. Inoculants are host-specific strains of *Rhizobia*. The efficacy of this process is dependent on the native population, the host plant and strain stability and the persistency and competitiveness of the inoculant strain (Amarger 2001).

2.1.2 N lifters

Crops which access and recover large quantities of soil mineral nitrogen (SMN) previously unavailable or leachable are referred to as “N lifters” and also “N holders” (Cuttle *et al.,* 2003).

Within mineral soils soil organic nitrogen (SON) accounts for 90% of the “total” N in the plough layer (Olk, 2008). Only 1-4% of SON is likely to become plant available (NH_4 and NO_3) annually (St. Luce *et al.,* 2011), as the turnover rates for differing fractions can be days to millennia (Kleber, 2010). Nitrate (NO_3) is highly mobile and soluble (Vos *et al*., 1998), therefore effective nitrate depletion is highly correlated with rooting depth as opposed to root density (Thorup-Kristensen, 2001), an important potential N-lifter species characteristic. Cherr *et al*., (2006) suggested non-legume green manure species such as rye (*Secale cereale*), mustards (*Brassica* spp.), buckwheat (*Fagopyrum esculentum* Moench) and *Phacelia* Juss. for this purpose. Brainard *et al.,* (2011) and Bergkvist *et al.,* (2011) suggests that N lifters are preferable to legumes in high fertility situations and overwintering in northern European temperate climate. Sainju and Singh (1997) found that green manure types significantly affected leaching levels with non-legumes consistently reducing leaching by 29-44% compared with legumes at a more variable 6-48%.

2.1.3 Plant mixtures as FBCs

Obviously, it is also possible, and very common, for farmers to sow mixtures of species. The success of this is dependent on matching growth habits; competitiveness and persistency. Mixtures of legumes or combinations of N fixers and N lifters can induce more aggressive nodulation and therefore increase N accumulation and yield, *via* increased fixation (Bergtold *et al*., 2005; Bergkvist *et al.,* 2011). Mixtures also offer the opportunity to manipulate species composition to match N release pattern to crops uptake requirements (The Organic Research Centre, 2011; Flower *et al.,* 2012)

2.2 Nitrogen accumulation by FBCs

FBCs have differing N accumulation potential, depending on uptake mechanism (N lifters, N fixers), soil characteristics, climate and cropping regimes (Brainard *et al.,* 2011). These influences are highlighted by the tables below and give an indication of FBCs potential N accumulation levels.

*2.2.1 Quantities of N accumul*ated

Quantities of N accumulated by temperate non-legume and legume for the species have been summarised by tables 2.1 and 2.2. For purposes of ease of interpretation the potential accumulation with intercropping has been excluded.

Table 2.1 N accumulation (kg N ha^{-1}) by temperate non-legume species.

Author and date	**Species**	**Annual N accumulation range (kg N ha^{-1})**
Jansen (1991)	Non legumes	10
Rannells and Wagger (1997c)	Rye (*S. cereale*) Wheat (*T. aestivum*)	18 North Carolina USA 39 North Carolina USA
Rannells and Wagger (1996)	Rye (*S. cereal)*	41 North Carolina USA
Francis *et al.*, (1998)	Fallow	42-45 New Zealand
N'Dayegamiye and Tran (2001)	Buckwheat (*F. esculentum*)	52-65 (4 months growth) Canada
N'Dayegamiye and Tran (2001)	Mustard (*Brassica hirta* Moench)	62-72 (4 months growth) Canada
Thorup-Kristensen (1994B; 2001) and Francis (1995)	Non legumes	200
Stopes *et al.*, (1996)	Ryegrass (*Lolium multiflorum* Lam)	15 – 346 (6-25 months) Clay loam – England
Constantin *et al.*, (2010)	White Mustard (*Sinapis alba*) Italian Ryegrass (*L. multiflorum)* Radish	97 and 29 (Conventional and No till) 35 37 and 34 (Conventional and No till)

Table 2.2 N accumulation (kg N ha^{-1}) by temperate legume species

Author and date	Species	Annual N accumulation (kg N ha^{-1}) range	Comments
Smith *et al*., (1985)	***Trifolium pratense L. (T. pratense)***	100-250	Sourced Frame, (2005)
Taylor and Quesenberry (1996)		76 – 389	Ontario, Canada Minnesota US
Vyn *et al*., (2000)		44 and 98	UK herbage crop
Vance (1997)		170	Annual figures, Minnesota US.
Peoples *et al*., (1995)[1-]		69-373	Fixation levels Collated data from various authors[1]
Owen (2000)	***Trifolium repens L. (T. repens)***	280	UK
Peoples *et al*., (1995)[2-]		54-291	Fixation levels Collated data from various authors[2]
Jørgensen *et al*., (1999)		100-150	(Yr 1 and Yr 2) Denmark
Høgh-Jensen and Schjoerring (1997)		262 and 211	6-25 month growth period England
Stopes *et al*., (1996)		17 – 592	6-25 month growth period England
Kumar and Goh (2002)		305	Above and below ground level. New Zealand
Stopes *et al*., (1996)	***Melilotus lupulina L. (M. lupulina)***	5 – 459	6-25 month growth period England
Rannells and Wagger (1992)	***Trifolium incarnatum L. (T. incarnatum)***	70	Herbage crop
Mueller and Thorup-Kristensen (2001)		111 and 77	(Yr 1 and Yr 2) Autumn sown Denmark
Torbet et al., (1996)		51 and 119	(Yr 1 and Yr 2) Alabama USA
Peoples *et al*., (1995)[3-]		24-185	Fixation levels Collated data from various authors[3]

Author and date	Species	Annual N accumulation (kg N ha^{-1}) range	Comments
	Vicia villosa* Roth. *(V. villosa)		
Mueller and Thorup-Kristensen (2001)		100-149	(Yr 1 and Yr 2) Autumn sown Denmark
Rannells and Wagger (1996)		154	(2 yr growth period) - North Carolina USA
La Rue and Patterson (1981)		184	
Cuttle and Goodlass (2004)		101-235	UK
Willumsen and Thorup-Kristensen (2001)		149	Denmark
Cuttle *et al.*, (2003)		121 (range 40-208)	UK fixation levels
Peoples *et al.*, (1995)[4-]		106	Fixation levels Collated data from various authors[4]
	***Lupinus* spp.**		
Vance (1997)	*L. angustifolius*	170	Minnesota US
Peoples *et al.*, (1995)	*L. angustifolius*	32-228	Fixation levels Collated data from various authors[5]
	Species unknown	46-199	Accumulation levels (Unkovich 1991)
		241-372	Accumulation levels (Unkovich *et al.*, 1994)
Cuttle *et al.*, (2003)	Species unknown	90-300	Fixation levels
Barrientos *et al.*, (2002)	*L. angustifolius* *L. albus*	192-282	Chile fixation levels
Espinoza *et al.*, (2012)	*L. angustifolius* *L. luteus*	87 115	Mean figures
Zotarelli *et al.*, (2012)	Species unknown	300	Fixation levels

Author and date	Species	Annual N accumulation (kg N ha^{-1}) range	Comments
Vance (1997)	***Pisum sativum* L. (*P. sativum*)**	72	Minnesota US
Peoples *et al.*, (1995)[6-]		17-244	Fixation levels
		200-227	Crop accumulated N Collated data from various authors[6]
Kucey (1989)		117	Western Canada
Sparrow *et al.*, (1993)		130	Alaska US
Cuttle and Goodlass (2004)		80-284	UK
Kumar and Goh (2002)		190	Above and below ground accumulation levels. New Zealand
Espinoza *et al.*, (2012)		396	Mean Chilean figures
	Mixtures		
Peoples *et al.*, (1995)[5-]	clover / vetch	50-370	Annual cropping
Francis et al., (1995)	White clover / ryegrass pasture	107-131	4 year ley New Zealand
Berntsen *et al.*, (2006)	White clover / ryegrass	490-545	4 year ley, on two sites in Denmark
Espinoza *et al.*, (2012)	Vetch / Oats	144	Mean Chilean figures

[1] Giller and Wilson (1991); Ledgard and Steele (1992); Peoples and Craswell (1992); Thomas (1995): Heichel et al., (1995)

[2-4-] Giller and Wilson (1991); Ledgard and Steele (1992); Peoples and Craswell (1992); Thomas (1995)

[5] Peoples and Craswell (1992); Herridge *et al.,* (1993); Peoples *et al.,* (1994a): Evans *et al.,* (1989)

[6] Peoples and Craswell (1992); Herridge *et al.,* (1993); Peoples *et al.,* (1994a): Jensen (1987)

This observed variation in BNF and accumulation may be attributed to cultivar potential (for example the selection of “Lupigen” *Lupinus albus* for experimentation in chapters 3 and 4), as well as to variations in soil N status and management practices in different climatic conditions (Stute and Posner, 1993; Fageria and Baligar, 2005; Zotarelli *et al.,* 2012). These factors induce differing responses within and between species i.e. on preferential uptake of inorganic N and efficacy of nodulation ultimately influencing BNF (Hardarson and Atkins, 2003; Hardarson *et al.,* 1991; Richards and Soper, 1979; Herder *et al.,* 2010; Espinoza *et al.,* 2012). Identification of high fixation potential FBCs thus should be a key agronomic selection criterion (Fageria, 2007).

As a benchmark, Ladha *et al*., (1988) concluded that legume FBCs accumulated 2.6kg N ha^{-1} day^{-1} over a period of time under ideal conditions, with annual dry matter (DM) production ranging from 1 to in excess of 10 t ha^{-1} (Lathwell. 1990) amassing under an established grass/clover ley a root/stubble biomass of about 10t DM ha^{-1} (Eriksen, 2001; Eriksen *et al*., 2004). The duration of a crop's growing period will affect the accumulation potential. Also, the effects of competition between grasses and clovers and the final proportion of legume and its effect on the C:N ratio of the interred material will affect subsequent release pattern.

2.2.2 Management factors affecting N accumulation

Even with a crop designated for N production, management can have a significant influence (Cuttle and Goodlass, 2004; Stute and Posner, 1993; Chirinda *et al.,* 2010). Poor FBC management can potentially influence soil properties, NUE and in turn crop production (Tonitto *et al.,* 2006; Chirinda *et al.,* 2010).

The practice of mulching can have a profound effect, particularly on legumes. The process of mulching, normally carried out in the absence of a livestock enterprise to utilise the crop, maintains the plants' vigour, normally occurring 3-6 times per year depending on species vigour (Hatch *et al.,* 2007). Mulching legume material returns high levels of N-rich residues to the soil (Cuttle and Goodlass, 2004). Preferential uptake of readily available N then occurs, retarding BNF (Joynes *et al.,* 2003; Hatch *et al.,* 2007; Loges *et al.,* 2000; Herder *et al.,* 2010) and potentially reducing N accumulation over the season (Cuttle and Goodlass. 2004).

For leguminous FBCs the single most useful agronomic practice to optimise yield potential is inoculation at establishment (Hardarson and Atkins, 2003). Efficient nodulation is fundamental to overall productivity of a leguminous crop (Espinoza *et al.,* 2012). Legume symbioses vary in their specificity (Broughton *et al.,* 2000; Day *et al.,* 2000; Graham and Vance, 2000; Pacios Bras *et al.,* 2000; Perret *et al.,* 2000). From a management perspective, the optimal way to ensure high levels of potential fixation is by the utilisation of “well” adapted species / cultivars to a given situation, as the native *Rhizobium* population will be prolific so as to induce profuse nodulation (Hardarson *et al.,* 1994). Obviously other managerial decisions influence species or cultivar decision making. If non-native species are to be introduced then inoculation is critical. Incorporation into the soil induces more profuse nodulation (Hardarson and Atkins, 2003), but the industry standard has become to inoculate the seed. This is the cheapest method, but the efficacy variation can be significant. For example Hardarson *et al.,* (1984) study on soyabeans indicated variation in levels of N fixation of 36-76% due to inoculation technique influencing the efficacy of nodulation.

Soil properties such as pH, moisture content, soil texture and nutrient status affect BNF levels (Stute and Posner, 1993; Chalk *et al.,* 2010, Kumar and Goh, 2000). Soil moisture deficiency can cause a major reduction in BNF of 70-80% reported by Ledgard et al., (1987) especially in shallow rooting perennials such as *T. repens* (Ledgard and Steele, 1992). Extreme acidity can induce aluminium (Al) and manganese (Mn) toxicity, affecting *Rhizobia* within the soil profile and fixation potential (Ledgard and Steele, 1992). Similarly worldwide deficiencies of phosphorus (P) and to some extent potassium (K) severly limits legume growth. Temperate *Trifolium* spp. display stunted growth poor root development and sub optimal BNF levels (Evans, 1977, Kumar and Goh, 2000) under deficient conditions.

2.2.3 Methods of assessment of N accumulation and soil N

The quantities of N recorded in the literature are dependent on the method of measurement. If only aboveground figures are utilised then it can underestimate or discount the contribution from the roots. Although lower in N, roots can still contribute significantly to total N uptake capacity (Thorup-Kristensen *et al.,* 2003, Chaves *et al.,* 2004; Neumann *et al.,* 2012)

Methods for measuring N fixation have been sources of discussion by numerous authors including Bergersen, (1980); Chalk and Ladha, (1999); Peoples *et al.,* (1989); Unkovich and Pate, (2000). Rough guides which are positively correlated with BNF are firstly, the quantity of DM produced by a legume and secondly the number and mass of nodules present on the roots (Espinoza *et al.,* 2012). An extension of this is a visual appraisal of the leghaemoglobin content of nodules (Frame, 2005). More precise methods include analysis of harvested material (Jørgensen and Ledgard, 1997; Frame, 2005; Peoples and Craswell, 1992) and isotope based methods (Hardarson and Dunso, 1993; Unkovich and Pate, 2000).

SON is the major naturally occurring source of N within soil; inorganic N is often referred to as soil SMN. SMN measurements are a measure of ammonium and nitrate N and can provide a “snapshot” of levels at that moment in time. Annual mineralisation rates vary (Bartholomew and Kirkham, 1960; St. Luce *et al.,* 2011), and the relationship between SOM accumulation and subsequent net release is complex because of intricate interactions of soil physical, chemical and climatic/seasonal conditions on microbiota (Nannipieri *et al.,* 1990; Antil *et al.,* 2001). Measurements of chemical indices of soil N availability have only poor or moderate correlation with plant uptake (Hong et al., 1990); better correlations have been obtained from aerobic and anaerobic soil incubation methods (Sanchez *et al.,* 2001).

Soil incubations tend to be a measure of potential mineralisable nitrogen (PMN). This is an expression of the SOM which is likely to be mineralised (Hassink, 1992) and is therefore a more useful measure of fertility over the forthcoming cropping season (Antil *et al.,* 2001). Hatch *et al.,* (1990) estimate that over an average growing season mineralisation predictions are about 50% higher than chemical extractions. Measurements of PMN may be laboratory or field based under aerobic or anaerobic conditions. Field based techniques such as incubated undisturbed soil cores or resin – core techniques have been proposed by Hatch *et al.,* (1991); Hook and Burke, (1995) and Bhogal *et al.,* (1999) and measure temporal changes in rates under field specific conditions (Bhogal *et al.,* 1999; Schomberg unknown; St. Luce *et al.,* 2011). This technique requires high levels of replication to mitigate spatial variation (Bhogal *et al.,* 1999).

Laboratory based PMN methods by their nature are difficult to extrapolate to field scenarios (Shepherd *et al.,* 1996) as they represent the maximum possible rate of mineralisation and are conducted under ideal conditions (Cabrera *et al.,* 1994; Honeycutt, 1999). Snapp and Borden (2005) suggested that laboratory PMN incubation did not represent maximum potential conditions. The anaerobic N mineralisation incubation method initially developed by Waring and Bremner (1964), has several advantages over aerobic incubation including faster sampling time as only NH_4 requires measurement and more N is mineralised over a given period from a smaller sample size. Optimising soil water content and temperature barriers are irrelevant in this technique (Lober and Reeder, 1993; St. Luce *et al.,* 2011). Results are also highly correlated with plant uptake (Waring and Bremner 1964; Ryan et al., 1971).

2.3 Nutrient release from incorporated residues

Figure 2.1 Simplified N cycle diagram

(Goulding, Pers Comm)

2.3.1 Underlying soil mechanisms

Once material enters the soil it undergoes chemical and physical transformations (Fageria 2007). Soil N availability is determined by a process known as mineralisation, i.e. the microbial mediated conversion of organic N to NH_4 with further oxidation to NO_3 (St. Luce *et al.,* 2011; Wedin and Tilman, 1990; Gil and Fick. 2001). This can have a fertilising effect on a following arable crop (Eriksen, 2001; Nevens and Reheul. 2002). N mineralization is regulated by the supply of above- and below-ground litter (Jenny, 1980) the quality, quantity and timing of incorporation of residues (Berendse *et al.,* 1989; Chirinda *et al.,* 2010; Monhanty *et al.,* 2011) and abiotic factors including soil moisture, temperature, pH and texture impacting on decomposer communities (Kumar and Goh, 2000; St. Luce *et al.,* 2011; Jenny, 1980). The conversion of organic to inorganic N is a source of plant available nutrients but if not fully utilised by the crop, losses via leaching may occur (Myrold and Bottomley, 2008; Watson *et al*., 1993; Eriksen *et al*., 1999).

Another process is the immobilisation of available N during the decomposition period, because the microbial population of the decomposing residues increases its biomass in response to the C source. If this occurs, the availability of NO_3 for plants may be substantially reduced and growth and development retarded (Dinnes *et al*., 2002).

2.3.2 Other factors determining residue breakdown.

Dramatic differences in potential N mineralization rates demonstrate the potential strong interactions between the composition of vegetation and N cycling (Mohanty *et al.,* 2011). For example in a study by Wedin and Tilman, (1990) grass species *Schizachyrium spp.* or *Andropogon spp.* exhibited mineralisation rates of 1-2g N m^{-2} y^{-1} compared with *Agrostis* spp. with levels of 12g N m^{-2} y^{-1} in the 3rd year. Wedin and Tilman, (1990) further indicated that differences in net N mineralisation rates, were highly correlated with below-ground litter quality and quantity to a greater extent than above-ground.

The effects of incorporation of residues were concluded by Mann, (1959) to be "short lived and unpredictable" However, subsequent work has attempted to define these unpredictable elements and their influence on residue behaviour within the soil matrix. Harris and Hesterman, (1990); Jensen, (1992); Ranells and Wagger, (1997c), and Jackson. (2000) concluded that the mineralisation of N from FBCs and the subsequent N assimilated by cash crops was dependent on the C:N ratio, soil type, and management practices. It is also important to remember that FBCs influence the soil N profile in advance of incorporation, via modifications in the growth phase, as it is depleted, or alters the SON content. (Thorup-Kristensen *et al.,* 2003).

2.3.3 Main influences on N supply for a succeeding crop

2.3.3.1 Pre-emptive competition

In this context the concept that mineralisation of the residues may not be sufficient to compensate for the effect of a crop's N uptake in the growth phase has been termed pre-emptive competition by Throup-Kristensen (1993b), although differing interpretations of the term are defined within Nguyen-Ngoc *et al.,* (2012). Examples of pre-emptive competition in this context have been described by Torstensson and Aronsson (2000), who demonstrated that before incorporation inorganic N was 25 kg N ha^{-1} lower in a catch crop than in the control. However, subsequent mineralization in this study was only 14 kg N ha^{-1}. These results were echoed by Francis *et al*., (1998) who found that a catch crop took up 200 kg N ha^{-1}, depleting soil inorganic N by 100 kg N ha^{-1}, and that subsequent mineralisation was not high enough to compensate.

Critical to determining pre-emptive competition is determining N retention within the soil. This is influenced by soil type, water holding capacity (WHC), precipitation and the rooting depth of the subsequent crop. For example pre-emptive competition would decrease and N supply would increase when followed by a shallow rather than by a deep rooting crop (Thorup-Kristensen and Nielsen, 1988; Willumsen and Thorup-Kristensen, 2001).

2.3.3.2 Subsequent N mineralisation

It can be concluded from a number of studies that that there are substantial variations in the rates of residue mineralisation. Breland (1994) indicated that about 50% of the residues from FBCs were mineralised in the first few months after incorporation. Dou *et al*., (1994) working in Pennsylvania, USA found rapid mineralisation (80%) 8 weeks post-incorporation. At the other end of the spectrum Thorup – Kristensen (2001) indicated that residue incorporation could induce immobilisation within the soil matrix, reducing N supply to subsequent crops in the first year (Thorup-Kristensen *et al.,* 2003). FBC rates of mineralisation varied from 10-78% of the added N in Mohanty *et al.,* (2011) study which corroborates the general consensus that observed variations can be attributed to residue quality, soil / climatic conditions and management practices (Harris and Hesterman. 1990; Jensen. 1992; Ranells and Wagger. 1997b; Jackson. 2000; Mohanty *et al.,* 2011)

2.3.4 Factors affecting N mineralisation

2.3.4.1 Residue Quality

The availability of soil N can be influences by the chemical composition of the interred crop residues (Vahdat *et al.,* 2011; Jensen *et al.,* 2005; Mohanty *et al.,* 2011; Verhulst *et al.,* 2011). FBCs' chemical composition changes dramatically after incorporation. Easily degradable water soluble carbohydrates and protein components decrease and more recalcitrant hemi-cellulose, cellulose and lignin increase (Kumar and Goh, 2000; Chirinda *et al.,* 2010; Mohanty *et al.,* 2011). Proportions vary with FBC age. Plants generally contain between 15-60% cellulose, 10-30% hemi-cellulose, 5-30% lignin, 2-15% protein and a small proportion of soluble substances (sugars, amino acids, amino sugars and organic acids) (Kumar and Goh, 2000). Other plant components are cutin, polyphenols and silicon (Si) (Gallardo and Merino, 1993; Cabrera *et al.,* 2005). Polyphenols may bind to soluble proteins and amino acids forming a compound resilient to decomposition (Kumar and Goh, 2000; Mohanty *et al.,* 2011). Lignin influences residues overall decomposition rate, attributed to lignin being a naturally recalcitrant substance that N-containing molecules may bind too, which inhibits / retards mineralisation (Vahdat *et al.,* 2011). Overall the rates of residue decomposition are dependent on the proportion of each fraction (St. Luce *et al.,* 2011; Mohanty *et al.,* 2011). Janzen and Kucey (1988) outlined a two phase decomposition process; phase one, being relatively rapid and dependent on initial residue N and phase two, relatively slower, regulated by lignin and polyphenol content.

2.3.4.2 Soil temperature and moisture effects

Soil temperature affects physical, biological and chemical reactions within the soil and the activity of micro-organisms, which in turn affect mineralization. Optimum soil temperature for growth and microbial activity is 25-35°C (Standford *et al.,* 1975). Generally N mineralisation is low below 5ºC and rapid at between 20-30 ºC (Cassman and Munn, 1980), although some field data indicates that rates of release can be rapid even under cold conditions (Breland, 1994; Thorup-kristensen 1994b; Van Schöll *et al*., 1997).

Temperature has differing degrees of influence on the decomposition of residues. Andersen and Jensen (2001) found that easily decomposable substrates (soluble sugars/ amino acids) were less affected at low temperatures than recalcitrant substances such as lignin. Ledgard and Steele (1992) indicated that gross rates of N mineralisation to immobilisation, decreased with temperature. In studies such as Anderson and Jenson (2001), immobilisation was retarded at low temperatures (3^{o}C and 9ºC) whereas mineralisation was only slightly hampered. From a management perspective the nitrification levels possible from crops such as black medic (*Medicago lupulina* L.*)* and white sweetclover (*Melilotus alba)* at 3ºC could lead to the potential for substantial leaching losses (Magid *et al*., 2001; Van Schöll *et al*., 1997).

Decomposition / mineralization is significantly slower under anaerobic than aerobic conditions (Kretzschmar and Ladd, 1993). Decomposition is limited by the rate at which oxygen can diffuse to the site of microbial activity. This is 10,000 times slower in water than air (Kumar and Goh, 2000). Hence soil moisture content plays a critical role in the rate of residue decomposition (Blantern 1991; Broadbent, 1986). Optimum soil WHC is between 50-80% field capacity (Whalen and Sampedro, 2010) rates of mineralization decreases at extreme WHC below <30% or in excess of >150% (Pal and Broadbent, 1975). These results agree with the drainage studies of Blantern (1991) where good drainage increased mineralisation rates by 2 and 2.6 times. However, if crop N recovery is insufficient leaching losses may increase

(Gill *et al.,* 1995). Thawing of a waterlogged frozen soil profile causes a release of soluble materials from immobilised microbial tissues, usually surface detritus, and in such conditions, in response to a surge of microbiological activity, the decomposition rate of residues may increase (Bunnell *et al.,* 1975; Witkamp, 1969).

2.3.4.3 Other soil factors

Changes in the behaviour of residues under differing soil characteristics are well understood (Cabrera *et al.,* 2005). Soil physical and chemical fertility properties such as compaction, temperature, porosity, acidity, the presence of toxic elements, and organic C, all have a bearing on microbial activity and residue breakdown (Grant *et al*., 1993; Thonnissen *et al*., 2000; Hassink *et al.* 1993; Ladd *et al.* 1996).

Predominant soil texture influences the physical and chemical properties discussed previously (Griffin, 2008; Subbarao *et al.,* 2006). OM levels influence the size and activity of the microbial population. One generalisation is the higher the OM content the greater the mineralisation potential (Sharifi *et al.,* 2008b). Generally organic residue decomposition is slower in high clay content soils compared with light textured soils (Griffin, 2008; Verbere *et al*., 1990). Reduced decomposition in clay content soils is attributed to higher aggregate surface area, poorer aeration and increasing SOM stabilisation potential, hence protecting OM from decomposition (Jenkinson 1977; Ladd *et al.,* 1996; Saggar *et al.,* 1996).

Soil pH, also has an impact on decomposition, by influencing micro organisms' population size and nature as well as the multiplicity of enzymes at microbial level (Kumar and Goh, 2000; Cabrera *et al.,* 2005; Subbarao *et al.,* 2006). Populations shift from bacteria (optimum pH 6.5-8) to actinomycetes to fungi (optimum 5.5-6.5) as pH declines (Alexander, 1980; Whalen and Sampedro, 2010) and retards decomposition rates. Alexander (1977) found that liming acid soils accelerated the decay of plant residues and SOM.

2.3.4.4 Management influences

Crop rotation, tillage and amendments with organic / inorganic material, affect N accumulation and significantly affect subsequent mineralisation (Sharifi *et al.*, 2008a; Verhulst *et al.,* 2011). Mechanical and chemical management can alter the quality, quantity and particle size distribution of incorporated residues and the degree of soil/residue amalgamation may significantly affect decomposition rates (Kumar and Goh, 2000; Verhulst *et al.,* 2011; Flower *et al.,* 2012). Other factors such as decomposition which occurs pre-incorporation e.g. from winter kill , glyphosate application (Snapp and Borden, 2005) or leaf litter shedding during the growth period, can all affect rates of decomposition (Thorup-Kristensen, 1994b). These processes have an impact on residue behaviour, as does the timing of agronomic practices where optimum timing may limit the fractions lost to leaching and assimilated by micro-organisms (Korsaeth *et al.,* 2002). Optimum residue management is an important way to improve N availability predictions as commercial farmers/ growers will use various methods to “check” FBC crops to facilitate incorporation.

The application of glyphosate, a non-selective, non-residual herbicide (British Crop Production Council (BCPC), 2012) induces root senescence and desiccation of tissues (Carlson and Donald, 1988). Glyphosate treatment reduced rye (*S. cereale*) root biomass to 115 gm^{-2} compared with 320 gm^{-2} untreated and shoot reduction to 80gm^{-2} compared to 200gm^{-2} untreated (Snapp and Borden 2005). Dessication enhances microbial access to residues thereby altering crop release pattern, as concluded by Vaughan and Evanylo (1998).

The effect of tillage at or post residue incorporation can also have a pronounced effect on residue behaviour within the soil matrix. Tillage enhances the breakdown of residues inducing higher levels of available N (Hardarson and Atkins, 2003), and having a fertilising effect on a subsequent arable crop (Berntsen *et al.,* 2006). Primary tillage to incorporate low C/N ratio residue (e.g. monoculture legumes) will induce very rapid net release of mineral N (Sarrantonio and Scott, 1988; Drinkwater *et al.,* 2000), leaving potentially large quantities of labile NO_3 in the profile which could be subject to leaching if conditions are conducive (Sarrantonio and Scott, 1988; Drinkwater *et al.,* 2000). Management strategies to mediate N leaching such as delaying primary cultivation, until later in the season (Korsaeth *et al.,* 2002) or spring incorporation rather than autumn, decreases the over winter risk (Stopes *et al.,* 1996) and provides better release/uptake synchronisation (Korseath *et al.,* 2002). On the other hand, strict no-till management may induce yield limitations due to immobilisation and a subsequent delay of N mineralisation relative to crop uptake (Sarrantonio and Scott, 1988; Varco *et al.,* 1989; Hardarson and Atkins, 2003; Schomberg *et al.,* 1994).

2.4 Environmental impact of the use of FBCs

2.4.1 Effects of FBCs on Leaching

Regardless of the form of N inputs, losses via leaching and denitrification can occur at crop removal or post-harvest (McCracken *et al.,* 1994; Thorup-kristensen *et al.,* 2003; Bergkvist *et al.,* 2011; Neumann *et al.,* 2012). Cover crops have the potential to increase retention of post-harvest surpluses (Tonitto *et al.,* 2006; Constantin *et al.,* 2010; Bergkvist *et al.,* 2011; Neumann *et al.,* 2012). They can reduce nitrate leaching in a number of ways; firstly by absorbing nitrate into their roots, thereby reducing the concentration in soil water; secondly by transporting nitrate upwards in the plant; and finally by reducing the amount of water percolating through the soil profile (Thorup-Kristensen *et al*., 2003). Tonitto *et al.*, (2006) found that the uptake from a non-leguminous cover crop was on average between 20 and 60 kg N ha $^{-1}$ of post-harvest N, equating to a reduction in N leaching of 40-70% as compared to a bare fallow, frequent cover crop utilisation in the long term can maintain nitrate concentration below 50mg L^{-1} (Constantin *et al.,* 2010).

However, after cover crop incorporation, this material may increase subsequent leaching if the soil conditions are conducive (Thomsen and Christensen. 1999; Wander *et al*., 1994). Stopes *et al.,* (1996) reported that post incorporation leaching levels over the winter period accumulated to a substantial 102kg $N0_3$ N ha^{-1} from a leguminous green manure. This suggests that legume based systems have the potential for BNF to far exceed harvested N exports in vegetation and grain and may leave labile N in the profile (LaRue and Patterson, 1981; Peoples *et al.,* 1995).

Leaching levels post incorporation are likely to be a function both of the levels of N accumulated and the residue release pattern. Both of these functions are reflections of individual FBC morphology. Stopes *et al.,* (1996) highlighted species' differential effects on leaching levels; red clover (*T. pratense*) leaching losses were 102kg $N0_3$ N ha^{-1} whereas perennial ryegrass (*L. perenne*) losses were 18kg $N0_3$ N ha^{-1} equating to 27% and 19% respectively of N accumulated in above ground material. This suggests that the use of red clover (*T. pratense*) or other leguminous species may lead to higher levels of labile NO_3 in the profile.

Species selection and incorporation timing are important measures which can limit the exposure of vulnerable N within the profile. Stopes *et al.,* (1996) and Philipps and Stopes, (1995) measured losses of 102 and 18kg No3 N ha^{-1} respectively for red clover and perennial ryegrass incorporated pre-winter compared with 26 and 4kg $N0_3$ N ha^{-1} for spring incorporation. Spring incorporation thus reduced the quantities of labile NO_3 in the profile.

As previously discussed reduction of leaching levels is a reflection of inherent morphology differences between N fixing and N lifting green manures. Legumes are generally considered less effective than non-legumes at accessing SMN (Vyn *et al*., 2000) but superior in lower fertility situations because of their fixation capacity (Vyn *et al*, 1999; 2000; Herder *et al.,* 2010).

2.4.2 Official Guidance on Fertiliser N Application

The current UK guidance on fertiliser recommendations is provided by the Fertiliser Manual (RB209) (DEFRA, 2010). RB209 calculates crop N requirement as being the quantity required to deliver on-farm economic optimum yields. The calculations are made on the basis of adequate water, soil type and sufficient supply of other nutrients, with reference to likely field spatial variability and field-specific cropping and manure management.

The foundation of N fertiliser recommendations is the soil nitrogen supply (SNS) index. This is an index from 0 – 6 which estimates the likely background N supply. SNS is derived via two possible methods, field assessment and measurement. The field assessment method takes account of the soil type, previous cropping and rainfall levels and ascribes N levels accordingly. The measurement method uses actual SMN levels, estimates of N within the crop and an estimate of likely mineralisable N deriving from SOM and crop debris during active crop growth (effectively PMN as described in 2.2.3). The field assessment method is described as being appropriate for the majority of arable rotations. However, the measurement method may give better results when SNS is suspected to lie outside of the normal range, for example, as a result of regular manure applications over previous seasons, or, as in the case of the trial described in chapter 4, the use of short term FBCs.

2.4.2.1 The Field assessment method

Soils are classified into 7 distinct groups, which cover soil texture, depth of topsoil and organic matter content. This classification underpins SNS and crop-specific recommendations, as N uptake efficiency for winter wheat and winter barley is calculated on the basis of soil classification; for example on shallow soils an NUE of 55% is assumed. “Previous cropping” does not provide options to simulate short term fertility building phases either as straight sown or undersown FBCs; the closest match appears to be main crop peas or beans. A modification of the RB 209 field vegetable crops system for N recommendation, using the size of crop (DM yield), N uptake and N supply (REF pages 237-239) may be appropriate for adaptation for simulating short term fertility building phases.

2.4.2.2 The measurement method

This method requires actual measurements of SMN, usually in early / late winter or early spring. February is the normal practice for winter wheat (R. Wootten. UAP Agronomist Pers. Comm.). Sampling is not conducted on peaty soils, established grassland or within the first year after grassland incorporation, and not within 2-3 months of fertiliser or manure applications. The profile is sampled to a depth of 90cm in spring crops, as the recommendation emphasises the importance of full N profiling. However on shallow soils, such as on the experimental site described in chapter 4, the topsoil is only approximately 30-40cms deep. To establish how much N is held within the crop, a series of techniques is used; GAI or crop height is used for oilseed rape and shoots per m^2 for winter wheat.

RB209 states that “Provided a recommendation system takes proper account of the total amount of N needed by a crop and of the supplies available from the soil and organic manures, it should give a recommendation close to crop N requirement”. This research may be able to refine this statement in light of the utilisation of short term FBCs. The lack of a provision in RB209 to offer recommendations following short term FBCs is an omission which could cause a lack of precision in fertiliser recommendations and which may hamper the adoption of this valuable technique. As well as hampering the associated enhanced economic and environmental sustainability under policy guidelines of good agricultural environmental conditions 1 and the soil protection review. This research may also be able further to inform the techniques / progression of RB209, which indicates that reliable estimates of mineralisable N from organic matter may be difficult to obtain, and that soil sample measurements of mineralisable N may be a viable option. This is a technique described by Lober and Reeder, (1993) utilised within this research and is further detailed in chapter 4 and appendix 1.3.

2.4.3 Species diversity

Sustainability in crop production now encompasses a desire for diversified rotations and biodiversity in cultivar selection (Commission on Sustainable Agriculture and Climate Change, 2012). Biodiversity of species helps to create environmentally and aesthetically acceptable agricultural practice (Enjalbert *et al.,* 2011). These outcomes are achieved by a buffering effect against climatic change, weed, pest and disease pressure and evolving agricultural practices (Enjalbert *et al.,* 2011; Hajjar *et al.,* 2008; Di Falco *et al.,* 2010).

Rotations diversified with FBCs may offer greater resilience to economic and environmental pressures, enhanced pollinator efficiency (Hajjar *et al.,* 2008), as well as modifying the weed community composition and dominance (Eyre *et al.,* 2011,) increasingly important, as EU regulation has reduced the availability of some chemistry (Agricultural Development Advisory Service (ADAS), 2008), as well as a lack of new modes of action (HGCA, 2010)

2.5 Rationale for experimental work.

FBCs have undergone renewed interest to facilitate environmental and economically sustainable farming (Fychan *et al.*, 2006) especially under the heavy economic impact of greatly fluctuating inorganic N fertiliser prices (Cherr *et al.,* 2006). Cuttle *et al.,* (2003) concluded that further research and clarity was required accurately to assess N availability from legumes in relation to the nutrition of subsequent crops. The emphasis for this research therefore is to refine and utilise some of the knowledge and principles of “organic” agriculture use of FBCs and to apply them to a conventional agricultural system.

The primary aim of FBCs is in the supply of nutrients to a subsequent crop and Cherr *et al.,* (2006) concluded that they possess the potential to have a significant impact on yield. However many authors such as Ladha *et al.,* (1996) and Singh *et al.,* (1991) found no consistent relationship between the use of FBCs and yield. This inconsistency in yield response may be related to the quantities of biomass and N accumulated and quality as estimated by C:N ratio. The literature supports this as both leguminous and non-leguminous green manures vary significantly in accumulation figures. Hence the accurate assessment of N accumulation and potential mineralisation under UK growing systems will be a fundamental component of this research.

Another key feature in FBC performance in terms of N accumulation is the response of different species to specific climatic, soil, and management conditions (Cherr *et al.,* 2006). As Thorup - Kristensen *et al.,* (2003) stated there appears to be very little efficacy data applicable to temperate areas and therefore this research intends to increase the provision of UK-applicable information.

Potential FBC species span a broad range of botanical genera with differing agricultural applicability from grain legumes to grazing plants. The majority have a C:N ratio of between 10 and 30, spanning the mineralisation / immobilisation balance point proposed by Thorup-Kristensen *et al.* (2003). A further element for investigation is the body of research concerning mixtures of FBC species. From a following crop nutrition perspective, the consequences from either mineralisation or temporal immobilisation of residues could be economically damaging to the farmer and environmentally detrimental. This information has informed the choice of the extensive range of FBC treatments (including a legume mixture) within the investigation. All display fundamental differences in morphology and usage. Detailed examination using a pot experiment was coupled with an extensive field trial. Ideally a pot experiment should precede the field trial and contain a very broad selection of species with the intention of critical evaluation. Because of time constraints concerning the investigations described in chapters 3 and 4, the pot experiment and field trials ran concurrently.

As management practices are a controllable element, it was felt that the investigation needed an attempt at increasing the understanding of how common practices may influence N accumulation and recovery. The timing of establishment and incorporation of green manure residues, particularly if cash crop establishment is delayed can ultimately impact on yield and profitability (Clark *et al.,* 1997; Thorup-kristensen *et al.,* 2003). Differences in seasonal incorporation patterns may leave the soil more predisposed to losses, for example pre winter incorporation as opposed to spring incorporation may increase the levels of highly vulnerable N in the profile potentially increasing leaching loss (Stopes *et al.,* 1996; Philipps and Stopes, 1995). This provides the basis for the decision to split test cropping into winter and spring sown varieties.

Investigations on release and uptake synchronisation should feature in view of their commercial applicability. Within the UK, one of the most widespread commercially utilised cash crops is winter wheat (*T. aestivum*) and Clothier (2001) attributed to this crop 61% of arable farmers' incomes. Fychan *et al.,* (2006) utilised winter and spring barley as test crops and indicated that spring cropping following spring cultivation was likely to be the best practice for recovery of N. In these trials however, winter and spring wheat will be used as test crops, better to reflect current cropping practices.

As environmental and practical interactions may discourage commercial usage of FBCs, modelling offers one potential solution (Arihara and Srinivasan. 2001). N accumulation and subsequent release has been subject to various models, each attempting to predict differing elements. The FBC model of Cuttle *et al*. (2003) is one example. This study will enable evaluation, further development and refinement of this model with information regarding a range of FBC species and cropping regimes.

Chapter 3, Pot Experiment

3.1 Introduction

The aim of this experiment was to gain a better understanding of the treatment species included in the field experiment described in chapter 4 and especially of their morphology, the contributions from above- and below-ground plant parts including nodulation efficacy, biomass and N yields and their suitability for incorporation into arable cropping systems. A suitable activity for assessing individual species traits and to aid the interpretation of field experimentation was thought to be the establishment of a pot experiment, featuring FBCs identified from literature as exhibiting desirable beneficial characteristics and being applicable in the UK and especially on the proposed trial site at Coates Manor Farm.

Pot experiments are featured within the literature and have been utilised for assessing N fixation (Amp, 2004) and species / cultivar viability (Brandon *et al.,* 1997). They have also been implemented as an integral part or as a precursor to a field experiment to aid understanding and interpretation, and examples of this include Rkert *et al*., (2001) and Bell *et al.,* (1997). However, Bell *et al.,* (1997) reported that the results found within a pot experiment were not always replicated in the field. In the experiment described in this chapter considerable efforts were made to reflect the field conditions as closely as possible.

The following review of literature is intended to provide the rationale for the selection of the range of FBCs for this investigation.

3.1.1 Types of FBCs – a rationale for selection

As already indicated in chapter 2 FBCs can fit into one of two main categories, N fixers and N lifters (or N holders (Cuttle *et al.,* 2003)). N lifters are crops capable of extracting large quantities of SMN into biomass, to act as temporary storage. Species already mentioned include rye (*Secale cereale*), mustard (*Brassica* spp.), buckwheat (*F. esculentum*) and *Phacelia* (Cherr *et al.,* 2006). Within this investigation *Phacelia* was included as a N lifter specialist crop because it is agronomically and environmentally attractive. *Phacelia* combines cold tolerance with rapid establishment and an extensive rooting system. It is thought to be highly applicable for UK agriculture as it is botanically unrelated to the *Cruciferae* family, and is very attractive to beneficial insects and bees (Cuttle *et al.,* 2003; Cotswold Seeds Ltd. 2010; Scarlett, 2011).

Natural regeneration fallow offered the opportunity to utilise residual inorganic N at the end of the growing season and (for a spring wheat test crop) N mineralised over the winter period (Thorup-Kristensen, 1994; Zagal *et al.,* 2001; Rodrigues *et al.,* 2002) without the cost implications of FBC establishment (Cuttle *et al.,* 2003; Promsakha Na Sakonnakhon *et al.,* 2006). It is, however, unpredictable in terms of composition, as it is dependent on previous cropping sequences, management and the existing weed seed bank (Eyre, *et al.,* 2011; Ekeleme *et al.,* 2003; Egley, 1986; Thompson and Grime, 1979). Composition of fallow will probably significantly affect residue quality and quantity and species germinating from the weed bank could display multiple botanical growth characteristics. A critical management element therefore is the prevention of seed shedding (Briggs, 2007). Promsakha Na Sakonnakhon *et al.,* (2006) showed that grass / mixed weed composition produced significantly more DM but significantly lower N content than legume / broadleaved weed composition. Natural regeneration fallow was included in this investigation to reflect the large areas so utilised following the advent of EU set-aside and agri-environmental schemes. It also provided a “control” “do nothing” treatment against which the effects of other FBCs could be compared.

As already mentioned in chapter 2 the main genera within the family *Legumionsae* include *Trifolium*; *Medicago*; *Lotus*; *Onobrychis*; *Ornithopus*; *Vicia*; *Hedysarum* and *Pisum* species (Frame, 2005). Within this array of species only a fraction has been investigated for their FBC potential (Fageria, 2007). Margins are enhanced economically following the use of high residue crops according to Bergtold *et al.,* (2005), providing an important incentive for FBC selection. Meelu *et al.,* (1994) suggested clovers (*Trifolium* spp.) and vetches (*Vicia* spp.) in temperate conditions, Tonitto *et al.,* (2006) recommended red clover (*Trifolium pratense* L.), crimson clover (*Trifolium incartnatum* L.) and hairy vetch (*Vicia villosa.* Roth) as well as cold-tolerant grain legumes as temperate green manures. The selections of legume plants for the investigation were made on the basis of specific attributes and botanical characteristics as detailed below.

3.1.2 Attributes of FBCs

Fageria (2007) recommended criteria that species should comply with to meet the dual aims of being agronomically attractive and economically viable. Species should be fast growing, so that autumn-sown crops establish prior to the main leaching period to remove excess nitrates from the profile, critical for reducing autumn losses. For spring sowing vigorous crop establishment is also critical to reduce potential weed invasion. Vigorous seedling development, critical for establishment, is demonstrated by crimson clover (*T. incarnatum*) and vetch (*V. villosa*) (Cuttle *et al.,* 2003; The Organic Research Centre, 2010; Frame, 2005). Legume species' biomass production and N accumulation vary under differing climatic conditions, crop age and management practices (Meelu *et al.,* 1994). This is the reasoning for the diverse range of species chosen for inclusion within this investigation design and for the inclusion of a mixed species treatment.

Species commonly found within UK farming agricultural systems include the perennial forage legumes white clover (*Trifolium repens.* L) and red clover (*T. pratense*), as well as grain legumes such as peas (*Pisum sativum.* L) and beans (*V. faba*) (Frame, 2005). These species are not grown exclusively for their FBC traits, but these are often an advantageous by-product of forage / arable cropping.

Species recognised within the literature as possessing suitable FBC traits, but which are not so widely used in UK agriculture at present include crimson clover (*T. incarnatum*) and vetch (*V. villosa*) which are native to southern Europe (Frame, 2005). *T. incarnatum.* is sometimes grown intercropped with maize (*Zea mays*) or as a component within multilevel grapes (*Vitis vinifera*) systems (Lloveras, 1987), whereas vetch is grown as an arable silage, usually with a cereal companion (Caballero, 1993). Both may also be grown as a summer annual in cooler northern latitudes (Hovelands and Evers, 1995), or over-winter in mild areas. Crimson clover possesses some frost resistance, but is generally not considered to be winter hardy (Brandsæter *et al.,* 2002). Vetch is described as cold hardy (Brandsæter *et al.,* 2002) and suitable varieties are available for autumn or spring drilling in the UK.

White sweetclover (*Melilotus albus* Medik) is the most extensively grown species within the *Melilotus* genus, and shares many characteristics with the yellow sweetclover (*Melilotus officinalis* (L) Pall) included within this experiment (Frame, 2005). These frost resistant species are commonly grown in North America as a green manure for soil improvement (Brandsæter *et al.,* 2002; Frame, 2005)

3.1.3 Botanical Characteristics of FBCs

Angus *et al.,* (2000) preferred annual species over perennial. Annual species included within the experiment were vetch (*V. villosa*); black medic (*M. lupulina*); peas (*P. sativum.*) lupins (*Lupinus. albus* L.) and *Phacelia*. These species fit well into a UK arable rotation, but greater flexibility for a longer term fertility-building phase would be given by biennials such as sweet clover (*M. officinalis*) or perennials such as white clover (*T. repens*) and red clover (*T. pratense*) (Cuttle *et al.,* 2003; Frame, 2005). The challenge, particularly in an arable context would be to maintain profitability within an extended legume phase. Furthermore the improved overwintering potential of biennials and perennials may extend the effective period of N fixation.

Growth habits and species attributes will determine their suitability for differing agricultural systems and are important assessments for commercial adoption. Grain legumes such as peas (*P. sativum.*) and lupins (*L. albus*) give the opportunity for a forage or cash crop. Forage crops can be either utilised for grazing, silage or hay crops. Potential species include crimson clover (*T. incarnatum.*), white clover (*T. repens*), red clover (*T. pratense.*) and sweet clover (*M. officinalis*). However *M. officinalis* may induce a livestock bleeding disease from spores which develop on hay or silage (Briggs, 2007; Cuttle *et al.,* 2003; Frame, 2005).

Bi-cropping or under-sowing is the process of growing multiple crops within a location at any one time. The literature identifies vetch (*V. villosa*) and peas (*P. sativum*.) and lupins (such as *L. albus*) as established bi-cropping components usually with a cereal for arable silage (Frame, 2005; Azo 2007). Other green manures suitable for under-sowing include sweet clover (*M. officinalis*), red clover (*T. pratense*.), white clover (*T. repens*.) and black medic (*M. lupulina*). Crimson clover (*T. incarnatum*) has been intercropped (Frame, 2005) and is widely used for this purpose in the USA, however Cuttle *et al.,* (2003) suggested that it is unsuitable for under-sowing as it is a poor competitor in bi-cropping stands.

Growth habits are important for management and harvesting (Fageria, 2007). Species exhibiting scrambling growth habits such as peas (*P. sativum.*) and vetch (*V. villosa*) (Frame, 2005), may cause mechanical harvesting problems, especially, for example, peas when lodged, (Cuttle *et al.,* 2003). Erectile growth habits such as exhibited by red clover (*T. pratense.*), crimson clover (*T. incarnatum.*), sweet clover (*M. officinalis*), *phacelia* and lupins (*L. albus*), may give more weed invasion potential due to a relatively open canopy compared to prostrate growth (Cuttle *et al.,* 2003; Frame, 2005; Soya UK, 2007). Prostrate species within the experimental design are black medic (*M. lupulina*) (Broddle, 2007), and stoloniferous white clover (*T. repens.*) (Frame, 2005). These species posses excellent ground coverage characteristics.

An integral part of a study of green manure crops is the study of below-ground biomass, N and C accumulation and nodule characteristics. Breland (1996b) indicated that root biomass of green manures may equate to 50% of the total biomass, but the levels will vary between species. Nitrogen content is relatively low in root biomass, accounting for 9-13% of total N accumulated by crimson clover (*T. incarnatum*) and hairy vetch (*V. villosa*.) (Meelu *et al.,*1990), Khan *et al.,* (2000) attributed more substantial figures to below-ground N contributions of between 26 and 68% of total plant N. Although below-ground contributions inputs per unit may be lower Thorup-Kristensen *et al.,* (2003) indicated levels are significant to the total N uptake capacity for following crops. For the purposes of field experiments with *T. repens* Jørgensen and Ledgard, (1997) and Korsaeth and Eltun, (2000) attached correction figures of 1.27 and 1.7 to be multiplied with above-ground figures to give a predicted level of total BNF accumulation by the plants.

The pot experimental approach gives the opportunity to access roots and to obtain a high level of recovery of the fine roots and root nodules. These are often underestimated due to the practicalities of sampling in the field (Koné *et al.,* 2008). Such data will be useful in the context of modelling (chapter 5) even though root growth may differ slightly between the two environments.

3.1.4 The Value of Mixtures

The literature indicates that species sown in mixtures appear to have an advantage over monocultures, due to improvements in the overall biomass of the mixed community (Tilman *et al.,* 1997) and macrofauna diversity and structure (Laossi *et al.,* 2008). Mixtures enhance the synergy between above and below-ground resource acquisition and assimilation processes, critical to sustain productivity and reduce losses (Chirwa *et al.,* 2003; Gathumbi *et al.,* 2002). A mixture of legumes (*M. officinalis.*, *T. pratense*.,*T. repens.*, *M. lupulina*) has been included as one of the treatments in this investigation.

3.2 Materials and Methods

Single plants representing all the species and cultivars used in the short term field trial in West Field on Coates Manor Farm were established in topsoil taken from West Field using individual pots and harvested at similar intervals to the West Field trial. Plants were destructively harvested in the autumn of

2007 and spring 2008, assessed and analysed, so as better to understand their morphology, nodulation and N accumulation properties and to inform the interpretation of the field trial.

3.2.1 Experimental Site

The experiment was sited on the library plots at the Royal Agricultural College (RAC), Cirencester OS grid reference SP 004 013. The trial was established within a protective frame (3.5m long x 2m wide x 2m high) designed to provide stability from the elements and protection from bird predation, as well as uniform growing conditions. The base was lined with a plastic membrane to prevent interactions between the underlying soil and the soil in the pots and the sides clad with bird proof netting. An irrigation system was also installed to provide supplementary mains water if required.

Plate 3.1 - Pot experiment (21st July 2007).

3.2.2 Treatments

The following species and cultivars were established with Certification1 (C1) generation seed on the 5th – 7th June 2007:

1 Natural regeneration fallow (weeds and volunteer crop plants allowed to germinate and establish from soil taken from West Field, Coates Manor Farm)

2 *L. albus.* white lupin cv. Dieta “Lupigen” (Soya UK Ltd.)

3 *T. incarnatum*. crimson clover cv. Contea

4 *M. lupulina*. black medic cv. Virgo Pajberg

5 *V. villosa*. Hairy vetch cv. Nitra

6 *M.* officinalis. yellow sweet clover cv. Commercial seed not certified as to variety

7 *T. pratense*. red clover cv. Milvus

8 *T. repens*. white clover cv Aberherald

9 A mixture of legumes (*M.* officinalis.cv [not specified], *T. pratense*. cv Milvus ,*T. repens*.cv. Aberherald, *M. lupulina*. cv. Virgo Pajberg.

10 *Phacelia* Juss. cv. Balo

11 *P. sativum*. field peas cv. Cooper

Seeds sourced from Cotswold seeds Ltd, Soya UK and Masstock Arable (UK) Ltd.

Harvest dates were August 28th- 29th 2007 and April 24th – 25th 2008

3.2.3 Experimental design

The treatments were arranged in an 11X 2 factorial randomised complete block design with six replicates of each treatment combination, totalling 132 “plots”.

All pots were placed within the frames and numbered with treatment numbers and located according to the randomisation plan. Extra *Phacelia* and fallow regeneration pots surrounded the trial to form a guard and to protect the integrity of the trial. A plan of the trial with detail of the randomisation of treatments is given at Appendix 2.4

Plate3.2 and 3.3 Illustrating species randomisation (28th July 2007).

3.2.4 Site preparation

Site preparation commenced 5th May 2007; with soil removed from West Field for establishment of the experiment. Soil samples were collected from 10 random positions within designated soil. The samples were bulked and sub sampled to give a representative sample and analysed for soil texture, pH, SON, soil P, soil K and Soil Organic Carbon (SOC) to provide baseline data.

Soil texture analysis was performed with a hydrometer in a suspended soil slurry Calgon solution (for full details see appendix 1.3) and the information plotted on a triangular texture chart. Soil pH was taken with a calibrated pH meter in a soil/water solution (for full details see appendix 1.3). SON and SOC were analysed by an Elementar Cube Carbon/Nitrogen/Sulphur (CNS) auto analyser. Soils were air dried, sub sampled, micro milled and weighed on a five place balance, 50mg (± 0.05 mg) of well mixed sample, with an equal weight of tungsten oxide encapsulated in aluminium or zinc foils (for full details see appendix 1.3).

Random samples of the seeds were extracted, in preparation for germination and vigour analysis in the laboratory. The techniques utilised were rolled towels and tray tests, both under cold regimes to simulate seedling development under adverse field conditions (for full details see appendices 1.1)(International Seed Test Association (ISTA), 1995).

The stone / clod content were excluded from the soil creating a “coarse” soil mixture. A proportion was removed and further sieved through a 1 cm sieve to produce a fine tilth for a seedbed prior to filling the pots.

Pots for this experiment were designed to split in half to give access to the root system at harvest, so as to be able to study the morphology and gain a higher recovery rate of root material. Pot dimensions were 60cm tall by 16cm diameter to allow root and biomass development. Pots were pressure washed to ensure no contaminants were present prior to being secured with duck tape.

3.2.5 Establishment

The trial was established on the 5-7th June 2007. 2 kg (± 0.05kg) of 20mm gravel (about 7cm height) of stone was added to the base of each pot to aid drainage. A further 9kg (± 0.05kg) of “coarse” soil was added, consolidated at 3 intervals with a weight during pot filling, followed by a further 1 kg (± 0.05kg) of sieved soil. Six seeds were sown per pot at species optimum sowing depth using a dibber. Species requiring a differing strain of *Rhizobium* to the native population for effective nodulation received the host specific strain at sowing in the form of an inoculant. Species receiving inoculation were White Lupin (*L. albus*) with *Bradyrhizobium lupinii* (Legume fix, Legume Technology Ltd.); Black Medic (*M. lupulina*) and Sweet Clover (*M.* officinalis with *Siniorhizobium meliloti. (*Legume fix, Legume Technology Ltd) Inoculants were mixed thoroughly with the seeds according to suppliers instructions; latex gloves were worn and disposed of between inoculants to reduce potential cross-contamination.

3.2.6 Management

Irrigation from a rain gun with mains water supplemented the natural rainfall, when periods of drought were suspected. During the course of the trial the addition of irrigation water only occurred at sowing.

An insecticide was applied on the 22nd June 2007, Dursban WG (active ingredient Chlorpyrifos) at 1kg/ha was applied in a spray volume of 200 l/ha. This provided wide spectrum of control on cutworms (*Agrotis segetum*), leatherjackets (*Tipula* spp.) and weevils (*Sitona lineatus*), which were thought to be a potential problem. In addition slug pellets in the form of Draza Forte (active ingredient methiocarb) were applied on the 14th July 2007 at a rate of 3.75kg/ha on the observation of low level damage. Molluscicide / insecticide application was applied in conjunction with manual removal of snails (*Helix aspera.*) and slugs (*Deroceras reticulatum*) from the pots. These applications were deemed necessary after visual examination of the pots within the experiment. No such applications were deemend necessary for the field trial in West Field.

Weeds were removed at the cotyledon growth stage (GS) (apart from the natural regeneration fallow treatment). Singling out of plants occurred on the 22nd August 2007 with the exception of the legume mixture where single plants of each constituent species were maintained.

Before the autumn / winter period the pots to be over-wintered and harvested in April 2008, were mulched. Mulching occurred on the 2nd October 2007, and species were cut to 5cm stubble. All of the above-ground biomass was cut into 5cm pieces (tolerance of 2cm) and returned to the pots to represent the action of a topper and the practices employed in the field trial in West Field.

3.2.7 Sampling and Harvest

One hundred and thirty two pots were established on the 7th of June 2007, 6 replicates of each green manure species were allocated to each harvest.

Irrespective of whether the green manure species failed to germinate or overwinter the same harvesting procedure was maintained. Each of the pots identified for harvest were removed from the protective frame. Pots were cut open and split in half, soil crumbled from the roots, and a well-mixed soil sample taken, labelled, and immediately removed to the refrigerators in the laboratory. The roots were then carefully washed / soaked to remove the soil and keep the root mass intact. The entire plant was then removed to the laboratory.

Table 3.1 Pot harvest sampling programme for the 2007/2008 period

Date	Description	Sample Description
07/06/07	132 Pots sown	
28-29/08/07	Pot Harvest (66 pots harvested)	Vegetation Soil
24–25 /04/08	Pot Harvest (66 pots harvested – 45 plants overwintered)	Vegetation Soil

3.2.8 Laboratory Assessment and Analysis

3.2.8.1 Assessment of nodules

Assessment of the legume species' nodules took place on 29th – 30th August 2007 and the 24th – 26th April 2008. Nodules were removed from the root mass with scalpels and tweezers under a magnified lamp onto a tile. Fresh weights (FW) and the numbers of individual nodules were recorded. Nodule activity was assessed by the exposure and reaction of leghaemoglobin to oxygen. This was achieved by squashing the nodules with the flat of a scalpel. On exposure to oxygen if a pinkish/brown stain was produced then nodules were deemed active. If green or brown stain was produced then the nodules were deemed inactive. The numbers of active and inactive nodules were recorded for each plant.

3.2.8.2 Plant tissue analysis

Plants were photographed and then split into components of roots and shoots. FWs of harvested material were taken, dried at 100ºC for 24hrs and then the dry weight recorded to give species components DM yield.

Nitrogen content in the roots and shoots as well as residue quality (C: N ratio) was analysed via an Elementar Cube CNS auto analyser. Plant tissue samples were dried. Samples were coarse milled (0.05mm gauze), then sub-sampled and further micro-milled to obtain a finely divided sample with a narrow particle size distribution. 25mg (± 0.05 mg) of well mixed sample plus equal weight of tungsten oxide were weighed on a five place analytical balance into aluminium or zinc foils. Encapsulated samples were then analysed on the auto analyser. (for full details see appendix 1.2).

3.2.8.3 Soil analysis

The soil samples were obtained from each pot, by hand crumbling soil away from the root system prior to root washing. Once in the laboratory, samples were assessed for SON and SOC on the Elementar Cube CNS auto analyser methodology as previously described (for full details see appendix 1.3) and for PMN (see appendix 1.3)

Soil PMN measurements were taken at harvest, a technique that required soil mineral N measurement, DM analysis and anaerobic incubation measurement (for full details see appendices 1.3). Samples were passed through a 6.7mm sieve, and any further visible plant material was removed. 50g (± 0.05g) of fresh soil was oven dried at 100ºC for 24hrs for DM analysis to adjust the N figures. Analytical replicates of each sample were weighed 25g (± 0.02g) into an extraction bottle, with 100ml of 0.5*M* $K_2SO_{4.}$ Samples were shaken and filtered through Whatman GFA 40 filter papers and the extracts then frozen in preparation for NH_4 and NO_3 analysis on FIA.

Potential mineralisation rates were determined by an anaerobic incubation method (Lober and Reeder. 1993) (See appendix 1.3)

3.2.9 Statistical Analysis.

Data were subjected to statistical analysis by means of Genstat 12th Edition (VSNi Ltd). Differences between treatments were established using the analysis of variance (ANOVA).

3.3 Results

Table 3.2 Pot experiment soil properties

Soil properties	Results
Soil Texture	Silty clay loam
Soil series	Sherborne
SOC	4.20 %
SON (t N ha^{-1})	11.97
pH	7.93 possible interference with Mn, B, Cu, Zn, Fe
P (mg / L)	46 (Index 4) Possible interference with Fe, Cu, Zn
K (mg / L)	337 (Index 3)

Laboratory germination and Vigour testing

Table 3.3 FBCs cold rolled towel technique germination and vigour test results

Species	**Vigour analysis* (% of the sample)**				**Germination percentage**
	Strong	**Fair**	**Weak**	**Failures**	
Lupin	48	23	17	12	88
Peas	70	17	6	7	93
Vetch	78	5	6	11	89
Phacelia	66	10	8	16	84
Mixture	72	16	6	14	86
Black medic	68	6	2	24	76
White Clover	88	5	4	3	97
Red Clover	83	9	5	3	97
Sweet Clover	55	12	2	31	69
Crimson Clover	59	16	8	17	83

* **Vigour analysis** – **Strong** – strong seedling with little or no damage

- **Fair** – generally normal seedling with slightly retarded development
- **Weak** – Seedlings with distinctly retarded and or abnormal development

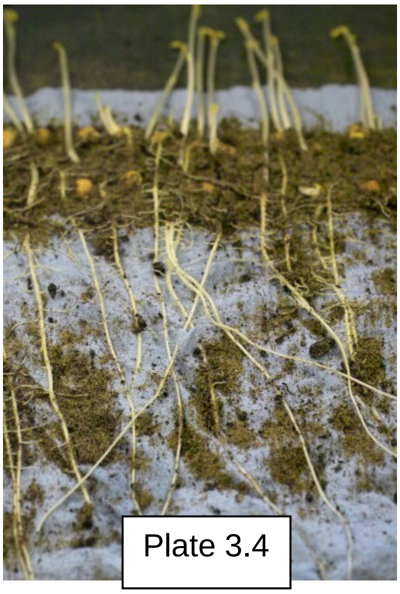


Plate 3.4

Plate 3.5

Plate 3.6

Plate 3.4 – Pea sample prior to germination / vigour assessment
Plate 3.5 – Lupin sample exhibiting strong vigour
Plate 3.6 – Crimson clover exhibiting poor seedling vigour

On seedling evaluation the lupin and pea seedlings appeared very dry, which was considered to have compromised their development, therefore a tray assessment was deemed more suitable.

Table 3.4 Tray technique vigour analysis

Species	% of plants displaying strong vigour*
Peas	70
Lupins	36
* **Strong Vigour**— strong seedlings with little or no damage	

Species displaying strong vigour, from 8 replicates of 50 seedlings.

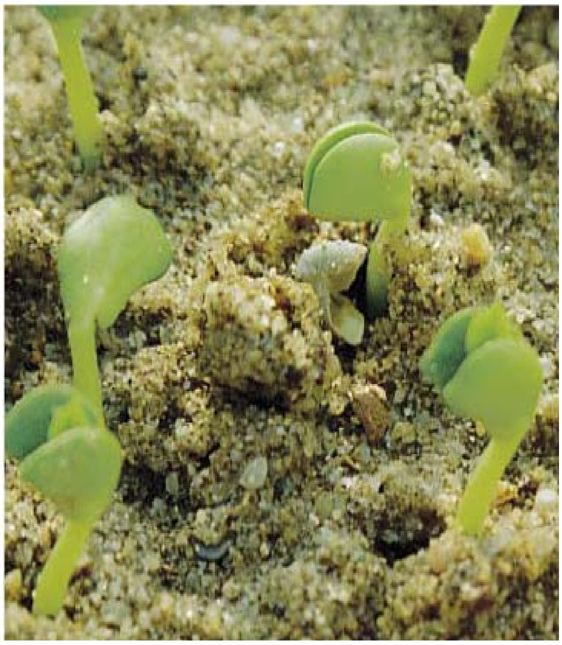


Plate 3.7 – Lupin sample within the tray vigour analysis.

3.3.1 Natural Regeneration Fallow

This comprises natural regeneration from the weed bank within the West Field sourced soil. The species harvested in 2007 were dandelions (*Taraxacum officinale*); timothy (*Phleum pratense*); black nightshade (*Solanum nigrum*); wheat (*T. aestivum*); blackgrass (*Alopecurus myosuroides*) and red dead nettle (*Lamium purpureum*). Species germinating or persisting in the pots until the 2008 harvest were blackgrass (*Alopecurus myosuroides*) and lambs tongue (*Plantago media*)

Plate 3.8

Plate 3.9

Plate 3.8 - Fallow specimen from pot 3 black nightshade
Plate 3.9 – Fallow specimens, Timothy and red dead nettle.

Table 3.5 Fallow results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	2.251	**Yield (g DM)**	3.42
% N	2.793	**% N**	2.266
% S	0.299	**% S**	0.181
% C	38.550	**% C**	39.844
C : N	13.8 : 1	**C : N**	17.6 : 1
Roots		***Roots***	
Yield (g DM)	0.467	**Yield (g DM)**	0.135
% N	1.106	**% N**	1.885
% S	0.122	**% S**	0.163
% C	34.025	**% C**	33.855
C : N	30.8 : 1	**C : N**	18.0 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	2.718	**Yield (g DM)**	3.555
% N	2.475	**% N**	2.224
% S	0.266	**% S**	0.179
% C	37.699	**% C**	39.182
C : N	15.3 : 1	**C : N**	17.6 : 1
N : S	9.3 : 1	**N : S**	12.5 : 1
Soil		***Soil***	
SOC (% C)	2.738	**SOC (% C)**	2.6281
SON (% N)	0.299	**SON (% N)**	0.288
PMN kg N ha^{-1}	116.11	**PMN kg N ha^{-1}**	67.36

3.3.2 White Lupin (*L. albus*) cv. Dieta "Lupigen"

White lupin is an erect annual grain legume, which grows best with a soil pH below 7 for good crop development and persistency of *Bradyrhizobium lupinii*. Watkins (2003) suggested that satisfactory growth can occur in soils with a higher pH. White lupin is a vigorous crop with thick stems and palmate leaves. In the UK it is mostly grown for forage (Soya UK 2008). This cultivar was developed for its nitrogen fixing properties, and as such was suitable for investigation (Soya UK, 2008). Seed was inoculated with "Legume fix" before sowing. This species, being an annual, did not recover from autumn cutting and mulching in 2007, therefore there was no plant data for spring 2008.

Table 3.6 White Lupin results table

Autumn 2007	
Shoots	
Yield (g DM)	9.912
% N	2.760
% S	0.167
% C	44.078
C : N	16.0 : 1
Roots	
Yield (g DM)	1.546
% N	1.099
% S	0.120
% C	35.895
C : N	32.7: 1
Whole Plant	
Yield (g DM)	11.458
% N	2.535
% S	0.143
% C	42.975
C : N	17.0 : 1
N : S	17.7 : 1
Nodules	
FW (g)	1.9742
Active	42.8
Inactive	0.4

Plate 3.11 Nodule assessment for *L. albus*

Plate 3.10 *L. albus* extracted from pot 17. Plant has flowered and produced small pods.

Soil (Autumn 2007)		**Spring 2008** ***Soil***	
SOC (% C)	2.83	SOC (% C)	2.594
SON (% N)	0.301	SON (% N)	0.282
PMN kg N ha^{-1}	156.39	PMN kg N ha^{-1}	60.59

3.3.3 Crimson clover (*T. incarnatum*) cv. Contea

This is an annual clover with a semi erect to erect growth habit arising from a crown rosette with hairy stems and leaves (Frame, 2005). Plants are acid tolerant but intolerant of poor drainage or salinity (Frame, 2005). *Rhizobium* association is with *Rhizobium leguminosarium* bv.*trifolii* which was provided by the soil's indigenous *Rhizobium* population (Amarger, 2001).

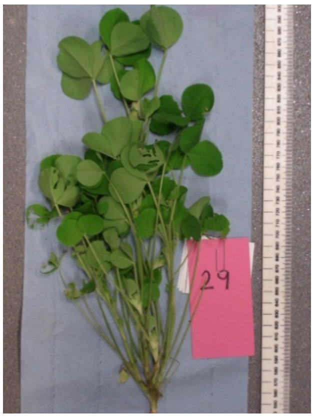


Plate 3.12 Crimson clover above ground biomass

Plate 3.13 Crimson clover within the West Field trial.

Table 3.7 Crimson clover results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	2.28	**Yield (g DM)**	6.727
% N	2.835	**% N**	2.506
% S	0.192	**% S**	0.199
% C	40.127	**% C**	41.396
C : N	14.2 : 1	**C : N**	18.2 : 1
Roots		***Roots***	
Yield (g DM)	0.262	**Yield (g DM)**	0.677
% N	1.849	**% N**	1.755
% S	0.248	**% S**	0.448
% C	39.922	**% C**	32.011
C : N	21.6 : 1	**C : N**	16.5 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	2.542	**Yield (g DM)**	8.793
% N	2.738	**% N**	2.434
% S	0.197	**% S**	0.222
% C	40.107	**% C**	40.796
C : N	14.7 : 1	**C : N**	16.9 : 1
N : S	13.9 : 1	**N : S**	11.2 : 1
Nodules		***Nodules***	
FW (g)	0.065	**FW (g)**	0.089
Active	131.4	**Active**	119
Inactive	19.8	**Inactive**	21.67
Soil		***Soil***	
SOC (% C)	2.738	**SOC (% C)**	2.626
SON (% N)	0.283	**SON (% N)**	0.280
PMN kg N ha^{-1}	132.76	**PMN kg N ha^{-1}**	99.53

3.3.4 Black Medic (*M. lupulina*) cv. Virgo Pajberg

This is a shade tolerant, low growing annual / perennial legume (Frame, 2005). *Rhizobium* association is with the same phylogenetic division as alfalfa (*Medicago sativa* L.) (Amarger. 2001; Gordon *et al.*,1995). *Sinorhizobium meliloti* is highly sensitive to soil acidity (Amarger, 2001) affecting crop productivity.

Plate 3.14 Black medic within the West Field trial

Plate 3.15. Black medic extracted from the 2008 pot harvest

Table 3.8 Black Medic results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	1.793	**Yield (g DM)**	6.728
% N	2.492	**% N**	3.029
% S	0.167	**% S**	0.228
% C	40.309	**% C**	39.916
C : N	16.2 : 1	**C : N**	13.2 : 1
Roots		***Roots***	
Yield (g DM)	0.375	**Yield (g DM)**	1.246
% N	1.975	**% N**	1.914
% S	0.209	**% S**	0.428
% C	35.614	**% C**	39.339
C : N	18.0 : 1	**C : N**	20.6 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	2.168	**Yield (g DM)**	7.998
% N	2.410	**% N**	2.855
% S	0.174	**% S**	0.259
% C	39.568	**% C**	39.815
C : N	16.4 : 1	**C : N**	15.2 : 1
N : S	13.9 : 1	**N : S**	11.0 : 1
Nodules		***Nodules***	
FW (g)	0.959	**FW (g)**	0.225
Active	71	**Active**	124.2
Inactive	0.5	**Inactive**	87.6
Soil		***Soil***	
SOC (% C)	2.656	**SOC (% C)**	2.697
SON (% N)	0.289	**SON (% N)**	0.292
PMN kg N ha^{-1}	148.3	**PMN kg N ha^{-1}**	88.43

3.3.5 Vetch (*V. villosa*) cv. Nitra

This is a hairy annual or biennial species with a scrambling or climbing growth habit, which is intolerant of shade, and drought in early GSs (Frame, 2005). It is suitable for a range of soils (Frame, 2005) and the associated *Rhizobium* is generally abundant 10^3-10^5 g $^{-1}$ although absent or at lower levels in acidic soils (Amarger, 2001).

Plate 3.16. Vetch within the West Field trial

Plate 3.17 Vetch plants in 2007 harvest

Table 3.9 Vetch results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	8.803	**Yield (g DM)**	0.19
% N	2.837	**% N**	3.669
% S	0.166	**% S**	0.202
% C	41.650	**% C**	39.312
C : N	14.7 : 1	**C : N**	10.7 : 1
Roots		***Roots***	
Yield (g DM)	0.435	**Yield (g DM)**	0.06
% N	1.754	**% N**	1.914
% S	0.256	**% S**	0.292
% C	33.889	**% C**	27.321
C : N	19.3 : 1	**C : N**	14.3 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	9.238	**Yield (g DM)**	0.25
% N	2.790	**% N**	3.001
% S	0.170	**% S**	0.230
% C	41.309	**% C**	35.894
C : N	14.8 : 1	**C : N**	13.9 : 1
N : S	16.5 : 1	**N : S**	13.1 : 1
Nodules		***Nodules***	
FW (g)	0.082	**FW (g)**	0.013
Active	60.17	**Active**	37.33
Inactive	11.5	**Inactive**	1
Soil		***Soil***	
SOC (% C)	2.684	**SOC (% C)**	2.739
SON (% N)	0.289	**SON (% N)**	0.300
PMN kg N ha^{-1}	148.91	**PMN kg N ha^{-1}**	66.56

3.3.6 Sweet Clover (*M. officinalis*)

This is an erect biennial species, which produces a single well branched succulent stem, which becomes increasingly fibrous over the season and redevelops from a crown in the second year (Frame, 2005). A similar species is white sweet clover (*Melilotus albus Medik.*). *M. officinalis* achieves effective nodulation with *Sinorhizobium meliloti* which is not common within UK soils. (Amarger, 2001). To increase the likelihood of effective nodulation and reduce the infection with inefficient strains, an inoculant was utilised.

Plate 3.18 and 3.19 Sweet clover above and below ground biomass

Table 3.10 Sweet clover results table

Autumn 2007		**Spring 2008**	
Shoots		***Shoots***	
Yield (g DM)	3.85	**Yield (g DM)**	2.198
% N	2.650	**% N**	3.327
% S	0.165	**% S**	0.202
% C	43.215	**% C**	39.045
C : N	16.3 : 1	**C : N**	11.7 : 1
Roots		***Roots***	
Yield (g DM)	1.312	**Yield (g DM)**	2.818
% N	2.404	**% N**	3.159
% S	0.121	**% S**	0.315
% C	39.609	**% C**	35.516
C : N	16.5 : 1	**C : N**	11.2 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	5.162	**Yield (g DM)**	5.016
% N	2.592	**% N**	3.197
% S	0.155	**% S**	0.285
% C	42.370	**% C**	36.9045
C : N	16.4 : 1	**C : N**	11.8 : 1
N : S	16.8 : 1	**N : S**	11.2 : 1
Nodules		***Nodules***	
FW (g)	0.150	**FW (g)**	0.079
Active	76.17	**Active**	25
Inactive	1.17	**Inactive**	59.6
Soil		***Soil***	
SOC (% C)	2.717	**SOC (% C)**	2.649
SON (% N)	0.293	**SON (% N)**	0.293
PMN kg N ha^{-1}	155.23	**PMN kg N ha^{-1}**	66.90

3.3.7 Red Clover (*T. pratense.*) cv. Milvus

Red clover is a short lived perennial, developing from a crown with a deep tap root for efficient water usage (Frame, 2005). A widespread worldwide temperate legume, fixation occurs with *Rhizobium leguminosarium.* bv. *Trifolii* presumed to be present in sufficient numbers within the native soil rhizobium. Suitable microsymbionts detected in a range of soils, pH 4.5 – 8 varied from 10^2-10^5 g^{-1} (Leung *et al*., 1994; Valdivia *et al*., 1988)

Plate 3.20. Red clover in the field experiment

Plate 3.21. Red clover plant extracted from the 2007 pot harvest

Table 3.11 Red clover results table

Autumn 2007		**Spring 2008**	
Shoots		***Shoots***	
Yield (g DM)	0.442	**Yield (g DM)**	4.39
% N	3.068	**% N**	3.041
% S	0.148	**% S**	0.215
% C	40.145	**% C**	40.187
C : N	13.1 : 1	**C : N**	13.2 : 1
Roots		***Roots***	
Yield (g DM)	0.227	**Yield (g DM)**	1.788
% N	2.145	**% N**	2.328
% S	0.236	**% S**	0.348
% C	36.114	**% C**	39.439
C : N	16.8 : 1	**C : N**	16.9 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	0.668	**Yield (g DM)**	6.178
% N	2.713	**% N**	2.825
% S	0.182	**% S**	0.253
% C	38.595	**% C**	39.937
C : N	14.3 : 1	**C : N**	11.8 : 1
N : S	15.1 : 1	**N : S**	11.2 : 1
Nodules		***Nodules***	
FW (g)	0.009	**FW (g)**	0.290
Active	48.17	**Active**	147.8
Inactive	6.67	**Inactive**	80.2
Soil		***Soil***	
SOC (% C)	2.634	**SOC (% C)**	2.554
SON (% N)	0.286	**SON (% N)**	0.282
PMN kg N ha^{-1}	126.06	**PMN kg N ha^{-1}**	55.55

3.3.8 White Clover (*T. repens*) cv. Aberherald

White clover is a perennial legume with a stoloniferous growth habit, excellent for colonising bare ground, but with greater susceptibility to water loss than other legumes (Frame, 2005). Majority of fixation is by *R. leguminosarium* bv. *trifolii*, but an association also occurs with symbiont *R. etli* (Eardly, 1993).

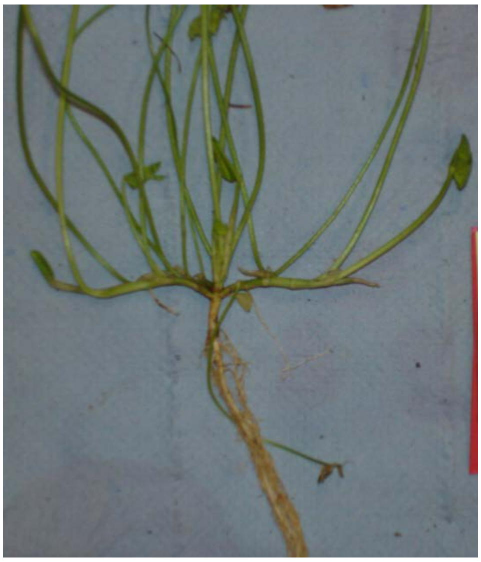


Plate 3.22. white clover in the field experiment.

Plate 3.23 white clover growth habit in the 2008 pot harvest

Table 3.12 White clover results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	0.252	**Yield (g DM)**	2.047
% N	3.683	**% N**	3.459
% S	0.236	**% S**	0.379
% C	38.270	**% C**	37.329
C : N	10.4 : 1	**C : N**	10.8 : 1
Roots			
Yield (g DM)	0.07	**Yield (g DM)**	0.457
% N	1.682	**% N**	1.893
% S	0.192	**% S**	0.451
% C	34.667	**% C**	36.21
C : N	20.6 : 1	**C : N**	19.1 : 1
Whole Plant			
Yield (g DM)	0.322	**Yield (g DM)**	2.692
% N	3.229	**% N**	3.142
% S	0.226	**% S**	0.393
% C	37.438	**% C**	37.093
C : N	11.6 : 1	**C : N**	14.2: 1
N : S	14.3 : 1	**N : S**	8.0 : 1
Nodules			
FW (g)	0.003	**FW (g)**	0.078
Active	15.33	**Active**	101.5
Inactive	2.5	**Inactive**	71.67
Soil			
SOC (% C)	2.675	**SOC (% C)**	2.514
SON (% N)	0.292	**SON (% N)**	0.283
PMN kg N ha^{-1}	147.69	**PMN kg N ha^{-1}**	46.35

3.3.9 Mixture

This was a mixture of four legume species, 40% red clover (*T. pratense*), 30% sweet clover (*M. officinalis*), 15% of both white clover (*T. repens*) and black medic (*M. lupulina*). *M. officinalis* and *M. lupulina* required the addition of *Sinorhizobium meliloti* to achieve effective nodulation (Amarger, 2001).

Plate 3.24. Mixture constituents extracted from the 2007 pot harvest. Left to right – Red clover, white clover, white clover, red clover.

Table 3.13 Mixture results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	0.681	**Yield (g DM)**	2.391
% N	3.296	**% N**	2.422
% S	0.179	**% S**	0.249
% C	40.548	**% C**	38.724
C : N	12.3 : 1	**C : N**	16.0 : 1
Roots		***Roots***	
Yield (g DM)	0.223	**Yield (g DM)**	1.232
% N	2.506	**% N**	3.033
% S	0.232	**% S**	0.384
% C	39.81	**% C**	40.190
C : N	15.9 : 1	**C : N**	13.3 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	0.908	**Yield (g DM)**	3.622
% N	3.113	**% N**	3.001
% S	0.192	**% S**	0.326
% C	40.374	**% C**	39.821
C : N	13.0 : 1	**C : N**	12.6 : 1
N : S	16.3 : 1	**N : S**	9.5 : 1
Nodules		***Nodules***	
FW (g)	0.007	**FW (g)**	0.049
Active	30.38	**Active**	107.23
Inactive	4.94	**Inactive**	45.23
Soil		***Soil***	
SOC (% C)	2.735	**SOC (% C)**	2.619
SON (% N)	0.302	**SON (% N)**	0.287
PMN kg N ha^{-1}	96.07	**PMN kg N ha^{-1}**	68.31

3.3.10 Phacelia cv. Balo

This is a non- leguminous N lifting green manure plant with rapid growth and extensive above and below-ground biomass.

Plate 3.25. Phacelia grown in the field experiment

Plate 3.26. Phacelia above ground biomass, extracted in the 2007 harvest

Table 3.14 Phacelia results table

Autumn 2007		Spring 2008	
Shoots		***Shoots***	
Yield (g DM)	5.346	**Yield (g DM)**	5.406
% N	1.462	**% N**	2.191
% S	0.153	**% S**	0.159
% C	39.804	**% C**	38.107
C : N	27.2 : 1	**C : N**	17.4 : 1
Roots		***Roots***	
Yield (g DM)	0.492	**Yield (g DM)**	1.00
% N	0.655	**% N**	1.795
% S	0.075	**% S**	0.384
% C	36.949	**% C**	29.699
C : N	56.4 : 1	**C : N**	16.5 : 1
Whole Plant		***Whole Plant***	
Yield (g DM)	5.838	**Yield (g DM)**	6.332
% N	1.403	**% N**	1.950
% S	0.147	**% S**	0.146
% C	39.590	**% C**	35.577
C : N	28.3 : 1	**C : N**	12.3 : 1
N : S	9.5 : 1	**N : S**	13.3 : 1
Soil		***Soil***	
SOC (% C)	2.582	**SOC (% C)**	2.688
SON (% N)	0.276	**SON (% N)**	0.334
PMN kg N ha^{-1}	118.6	**PMN kg N ha^{-1}**	57.75

3.3.11 Peas (*P. sativum.*) cv. Cooper

Field pea is a rapid growing glabrous annual with angular or roundish hollow stems which possess a scrambling growth habit which leaves it predisposed to lodging (Frame, 2005). *P. sativum* displays a higher degree of selectively towards its symbiotic bacteria *Rhizobium leguminosarium* bv. *Viciae* than other species infected by this group (Amarger, 2001). *Rhizobium leguminosarium* bv. *Viciae* is found within the majority of soils except acidic ones. Therefore *P. sativum* within this experiment relied on the native soil population (Amarger, 2001). This species, being an annual did not recover from autumn cutting and mulching in 2007 and there was therefore no plant data for spring 2008.

Table 3.15 Peas results table

Autumn 2007	
Shoots	
Yield (g DM)	8.105
% N	2.390
% S	0.108
% C	43.604
C : N	18.2 : 1
Roots	
Yield (g DM)	0.26
% N	1.817
% S	0.259
% C	35.212
C : N	19.4 : 1
Whole Plant	
Yield (g DM)	8.365
% N	2.373
% S	0.113
% C	43.351
C : N	18.3 : 1
N : S	21.2 : 1
Nodules	
FW(g)	0.0632
Active	38.67
Inactive	13.83
Soil	
SOC (% C)	2.909
SON (% N)	0.299
PMN kg N ha^{-1}	139.47

Plate 3.27. Peas at pod set in the field experiment.

Plate 3.28. Pea specimen harvested 2007

Spring 2008	
Soil	
SOC (% C)	2.652
SON (% N)	0.408
PMN kg N ha^{-1}	55.78

3.3.12 FBCs DM yields results

Complete tables of results comparing all treatments are available in appendices 3.1.2 to 3.1.7.

Table 3.16 Autumn 2007 FBCs DM yield (g)

Autumn 2007 DM yield (g)						
FBCs	**Shoots**		**Roots**		**Whole plant**	
Fallow	2.251	cde	0.4667	abcdefgh	2.718	def
White Lupin	9.912	j	1.546	j	11.458	k
Crimson Clover	2.28	def	0.262	abcde	2.542	de
Black Medic	1.793	abc	0.375	abcdef	2.168	bcd
Vetch	8.803	ij	0.435	abcdefg	9.238	ij
Sweet Clover	3.85	fg	1.3117	j	5.162	g
Red Clover	0.442	ab	0.2267	abc	0.668	ab
White Clover	0.252	a	0.07	a	0.322	a
Mixture	0.681	abc	0.2225	ab	0.903	abc
Phacelia	5.346	gh	0.492	abcdefghi	5.838	gh
Peas	8.105	i	0.26	abcd	8.365	i
SED		**0.7929**		**0.2218**		**0.9243**
LSD (P<0.05)		**1.584**		**0.443**		**1.536**

The highest ($P<0.05$) DM yields of above ground biomass were exhibited by annual FBCs peas (*P. sativum)* vetch (*V. villosa*) and white lupin (*L. albus*), the lowest levels were exhibited by the perennials black medic (*M. lupulina*), red clover (*T. pratense*), white clover (*T. repens*) and the mixture. Biennial sweet clover (*M. officinalis*) and white lupin (*L. albus*) demonstrated significantly ($P<0.05$) higher levels of below ground biomass production than all other FBCs. FBCs overall whole plant biomass was greatest ($P<0.05$) from annual grain legumes white lupin (*L. albus*) peas (*P. sativum*), followed by biennial sweet clover (*M. officinalis*) and non legume *Phacelia.*

Table 3.17 Spring 2008 FBCs DM yield (g)

Spring 2008 DM yield (g)						
FBCs	**Shoots**		**Roots**		**Whole plant**	
Fallow	3.42	abcde	0.135	ab	3.555	abc
Crimson Clover	6.727	e	0.6767	abcd	8.793	e
Black Medic	6.728	e	1.246	abcdefg	7.998	cde
Vetch	0.19	a	0.06	a	0.25	abc
Sweet Clover	2.198	abc	2.818	h	5.016	bcde
Red Clover	4.39	bcde	1.788	defgh	6.178	bcde
White Clover	2.047	ab	0.4567	abc	2.692	ab
Mixture	2.391	abcd	1.2316	abcdef	3.622	abcd
Phacelia	5.406	bcde	1	abcde	6.332	bcde
SED		**1.68**		**0.7059**		**2.305**
LSD (P<0.05)		**3.401**		**1.429**		**4.667**

The FBCs which overwintered successfully in terms ameliorating significantly greater levels (P<0.05) of above ground biomass were crimson clover (*T. incarnatum*), black medic (*M. lupulina*), red clover (*T. pratense*) and non-legumes *Phacelia* and fallow. Sweet clover (*M. officinalis*) demonstrated high levels of below ground root production in both the autumn of 2007 harvest (table 3.16) and the spring of 2008, significantly (P<0.05) out yielding all other FBCs with the exception of red clover (*T. pratense*) in 2008. Annual vetch (*V. villosa*) demonstrates low levels of biomass production in all of the spring 2008 parameters, the whole plant biomass levels were comparable with fallow, white clover (*T. repens*) and the mixture.

3.3.13 Leguminous FBCs nodule results

Table 3.18 Autumn 2007 leguminous FBCs nodule assessment

Autumn 2007 Nodule assessment						
FBCs	**Fresh weight**		**Active**		**Inactive**	
White Lupin	1.9742	i	42.8	abcd	0.4	a
Crimson Clover	0.0649	abcdef	131.4	h	19.8	gh
Black Medic	0.0959	abcdefg	71	abcdefg	0.5	ab
Vetch	0.0816	abcdef	60.17	abcdef	11.5	abcdefg
Sweet Clover	0.1496	defgh	76.17	bcdefgh	1.17	abc
Red Clover	0.0089	abc	48.17	abcde	6.67	abcdef
White Clover	0.0029	a	15.33	a	2.5	abcd
Mixture	0.0069	ab	30.38	ab	4.94	abcde
Peas	0.0632	abcd	38.67	abc	13.83	efgh
SED	**0.06534**		**28.68**		**5.618**	
LSD (P<0.05)	**0.1311**		**57.53**		**11.27**	

Leguminous FBCs producing the highest (P<0.05) fresh weigh yield of nodules were white lupin (*L. albus*), the lowest yields were demonstrated by annuals peas (*P. sativum*), crimson clover (*T. incarnatum*), vetch (*V. villosa*) and the perennials white clover (*T. repens*), red clover (*T. pratense*) and the mixture. Crimson clover (*T. incarnatum*) exhibited the greatest levels of nodule activity and inactivity in the 2007 assessment, significantly greater than the other FBCs with the exception of sweet clover (*M. officinalis*) (active) and peas (*P. sativum*) (inactive).

Table 3.19 Spring 2008 leguminous FBCs nodule assessment

Spring 2008 Nodule assessment			
FBCs	**Fresh weight**	**Active**	**Inactive**
Crimson Clover	0.08907 abcde	119 a	21.67 a
Black Medic	0.22522 ef	124.2 a	87.6 b
Vetch	0.01337 a	37.33 a	1 a
Sweet Clover	0.07908 abcd	25 a	59.6 a
Red Clover	0.29048 f	147.8 b	80.2 a
White Clover	0.07795 abc	101.5 a	71.67 a
Mixture	0.04905 ab	107.23 a	45.23 a
SED	**0.06945**	**58.13**	**40.75**
LSD (P<0.05)	**0.1413**	**118.3**	**82.91**

Black medic (*M. lupulina*) and red clover (*T. pratense*) exhibited the greatest fresh weight yield of nodules in 2008 harvest. However, their nodules characteristics differed, with black medic (*M. lupulina*) exhibited significantly (P<0.05) higher levels of inactivity and red clover (*T. pratense*) with significantly (P<0.05) higher levels of activity than all other FBCs.

3.3.14 FBCs quality attributes

3.3.14.1 Autumn 2007 harvested FBCs

Table 3.20 Autumn 2007 FBCs shoots quality characteristics

Autumn 2007 Shoots attributes								
FBCs	**% N**		**% C**		**% S**		**C:N ratio**	
Fallow	2.793	ef	38.55	b	0.299	k	13.8	d
White Lupin	2.760	e	44.08	k	0.147	b	15.97	f
Crimson Clover	2.835	efg	40.13	d	0.192	hi	14.15	de
Black Medic	2.492	c	40.31	f	0.167	defg	16.18	f
Vetch	2.837	fgh	41.65	h	0.166	def	14.68	e
Sweet Clover	2.650	d	43.21	i	0.165	de	16.31	f
Red Clover	3.067	i	40.15	de	0.148	bc	13.09	c
White Clover	3.683	k	38.27	a	0.236	j	10.39	a
Mixture	3.296	j	40.55	g	0.179	efgh	12.3	b
Phacelia	1.462	a	39.80	c	0.153	bcd	27.28	h
Peas	2.390	b	43.60	j	0.108	a	18.25	g
SED	**0.035**		**0.042**		**0.007**		**0.513**	
LSD (P<0.05)	**0.077**		**0.092**		**0.016**		**1.129**	

FBCs exhibiting the highest N percentage in their shoots were perennials white clover (*T. repens*), red clover (*T. pratense*) and the mixture and the lowest levels by *Phacelia* and peas (*P. sativum*). The highest C percentage was demonstrated by annual and biennial FBCs. From a residue quality perspective the relationship between the carbon and nitrogen is of interest. Phacelia has a relatively low %C and N, this equates to a C: N ratio significantly (P<0.05) greater than all other FBCs and above the suggested mineralisation immobilisation balance point. In general non legume Phacelia and annual grain legumes have C: N ratios significantly (P<0.05) greater than the perennial or biennial species. Sulphur content within the shoots varied between FBCs, the highest levels (P<0.05) were demonstrated by fallow, and the lowest (P<0.05) by peas (*P. sativum*).

Table 3.21 Autumn 2007 FBCs roots quality characteristics

Autumn 2007 Roots attributes				
FBCs	**% N**	**% C**	**% S**	**C:N ratio**
Fallow	1.106 bc	34.03 ab	0.122 bcd	30.77 f
White Lupin	1.099 b	35.90 f	0.119 b	32.67 f
Crimson Clover	1.849 efg	39.92 j	0.248 ghi	21.59 e
Black Medic	1.975 gh	35.61 e	0.209 ef	18.03 bc
Vetch	1.754 de	33.89 ab	0.256 hij	19.32 cd
Sweet Clover	2.404 j	39.61 i	0.121 bcd	16.48 a
Red Clover	2.145 i	36.11 fg	0.236 gh	16.84 ab
White Clover	1.682 d	34.67 c	0.192 ef	20.61 de
Mixture	2.506 j	39.81 ij	0.232 g	15.93 a
Phacelia	0.655 a	36.95 h	0.075 a	56.55 g
Peas	1.817 ef	35.21 d	0.259 ij	19.38 d
SED	**0.060**	**0.116**	**0.010**	**1.313**
LSD (P<0.05)	**0.132**	**0.255**	**0.022**	**2.89**

N levels within the root biomass were lower than above ground levels, as with the above ground biomass the perennial and biennial FBCs exhibit the highest ($P<0.05$) N levels, with the exception of white clover (*T. repens*) which were comparable with annual legumes. FBCs with significantly ($P<0.05$) elevated percentage carbon within root biomass were the mixture and crimson clover (*T. incarnatum*), whereas vetch (*V. villosa*) and the fallow species demonstrated significantly lower ($P<0.05$) levels. The C: N ratio for below ground material indicated that five of the FBCs (*Phacelia*, *L. albus*, fallow, *T. incarnatum* and *T. repens*) were in excess of the suggested 20:1 balance point ratio. Sulphur levels were lowest within *Phacelia* root biomass and significantly ($P<0.05$) higher within the peas (*P. sativum*) and vetch (*V. villosa*) biomass.

Table 3.22 Autumn 2007 FBCs whole plant quality characteristics

Autumn 2007 Whole plant attributes					
FBCs	**% N**	**% C**	**% S**	**C:N ratio**	**N:S ratio**
Fallow	2.48 bcd	37.70 ab	0.266 k	15.27 ef	9.31 a
White Lupin	2.54 cde	42.98 j	0.143 b	16.95 ghi	17.73 ij
Crimson Clover	2.74 gh	10.11 e	0.197 hi	14.65 cd	13.91 cd
Black Medic	2.41 bc	39.57 d	0.174 ef	16.42 gh	13.89 c
Vetch	2.79 hi	41.31 h	0.170 e	14.81 cde	16.47 gh
Sweet Clover	2.59 def	42.37 i	0.155 bcd	16.35 g	16.78 ghi
Red Clover	2.71 fg	38.60 cd	0.182 fg	14.28 c	15.15 cdef
White Clover	3.23 j	37.44 a	0.226 j	11.63 a	14.28 cde
Mixture	3.11 j	40.37 efg	0.192 gh	12.98 b	16.26 fg
Phacelia	1.40 a	39.59 de	0.147 bc	28.28 k	9.53 ab
Peas	2.37 b	43.35 j	0.113 a	18.27 j	21.17 k
SED	**0.0064**	**0.203**	**0.0058**	**0.338**	**0.624**
LSD (P<0.05)	**0.127**	**0.406**	**0.0116**	**0.666**	**1.246**

Whole plant quality characteristics is representative of the interred material, the FBCs exhibiting the highest percentage N in excess of 3% and significantly (P<0.05) lower C: N ratio than the other FBCs were white clover (T. repens) and the mixture. Conversely, peas (*P. sativum*) and *Phacelia* demonstrated significantly (P<0.05) lower N levels and the widest C: N ratios of the FBCs. Annual crops (*P. sativum, L. albus, V. villosa*) and biennial (*M. officinalis*) produced significantly (P<0.05) higher levels of C within their whole plant biomass than the perennial species. The influence of the whole plant percentage sulphur is reflected in the N: S ratio, fallow and peas (*P. sativum*) demonstrated significantly (P<0.05) higher and lower sulphur levels than the other FBCs, which produced the narrowest and widest of C: N ratios.

3.3.14.2 Spring 2008 harvested FBCs

Table 3.23 Spring 2008 FBCs shoots quality characteristics

Spring 2008 Shoots attributes				
FBCs	**% N**	**% C**	**% S**	**C:N ratio**
Fallow	2.266 ab	39.84 bcde	0.181 ab	17.58 g
Crimson Clover	2.506 abc	41.40 e	0.199 abc	16.52 defg
Black Medic	3.028 bcd	39.92 bcde	0.228 abcdef	13.37 abcde
Vetch	3.669 d	39.31 abcd	0.202 abcd	10.76 a
Sweet Clover	3.327 d	39.04 abc	0.248 abcdefg	12.28 abc
Red Clover	3.041 cd	40.19 cde	0.215 abcde	13.25 abcd
White Clover	3.459 d	37.33 a	0.379 i	10.79 ab
Mixture	3.033 bcd	40.19 cde	0.249 abcdefgh	13.52 abcdef
Phacelia	2.191 a	38.11 ab	0.159 a	17.64 g
SED	**0.03656**	**0.9772**	**0.06148**	**1.682**
LSD (P<0.05)	**0.7713**	**2.062**	**0.1297**	**3.548**

The perennial species combined with vetch (*V. villosa*) and sweet clover (*M. officinalis*) produced the highest (P<0.05) levels of N within above ground biomass, in general these FBCs exhibited the lowest % C with the exception of black medic (*M. lupulina*), red clover (*T. pratense*) and the mixture. *Phacelia* exhibited a low percentage C as it regenerated from shed seed and was relatively immature in comparison with the other FBCs. The C: N ratio for all FBCs was below the balance point, significantly (P<0.05) wider C: N ratio were displayed by *Phacelia*, fallow and crimson clover (*T. incarnatum*) (17.64; 17.58; 16.52:1 respectively). White clover (*T. repens*) demonstrated significantly (P<0.05) higher levels of S than all the other FBCs.

Table 3.24 Spring 2008 FBCs roots quality characteristics

Spring 2008 Roots attributes				
FBCs	**% N**	**% C**	**% S**	**C:N ratio**
Fallow	1.885 [abc]	33.86 [ab]	0.163 [a]	17.69 [bc]
Crimson Clover	1.755 [a]	32.01 [ab]	0.448 [c]	18.24 [bc]
Black Medic	1.914 [abcde]	39.34 [b]	0.428 [c]	20.56 [c]
Vetch	1.914 [abcdef]	27.32 [a]	0.292 [abc]	14.27 [ab]
Sweet Clover	3.159 [g]	35.52 [ab]	0.315 [abc]	11.25 [a]
Red Clover	2.328 [abcdefg]	39.44 [b]	0.348 [bc]	16.94 [bc]
White Clover	1.893 [abcd]	36.21 [ab]	0.451 [c]	19.13 [bc]
Mixture	2.422 [abcdefg]	38.72 [ab]	0.384 [c]	16.83 [bc]
Phacelia	1.795 [ab]	29.70 [ab]	0.205 [ab]	17.62 [bc]
SED	**0.5553**	**5.48**	**0.07847**	**2.091**
LSD (P<0.05)	**0.443**	**11.84**	**0.1695**	**4.518**

The 2008 root biomass N levels were significantly (P<0.05) greater in sweet clover (*M. officinalis*) biomass with the exception of red clover (*T. pratense*) and the mixture. Vetch exhibited the lowest percentage C in below ground root biomass, this low C contributes towards the narrow C: N ratio which is significantly (P<0.05) lower than all the other FBCs with the exception of sweet clover (*M officinalis*). As with the above ground biomass white clover (*T. repens*) demonstrates the highest sulphur levels (0.451%) significantly (P<0.05) greater than fallow, *Phacelia*, vetch (*V. villosa*) and sweet clover (*M. officinalis*).

Table 3.25 Spring 2008 FBCs whole plant quality characteristics

Spring 2008 Whole plant attributes					
FBCs	**% N**	**% C**	**% S**	**C:N ratio**	**N:S ratio**
Fallow	2.22 ab	39.18 e	0.179 ab	17.62 g	0.080 c
Crimson Clover	2.43 bc	40.50 e	0.222 c	16.36 fg	0.091 bc
Black Medic	2.86 cd	39.82 e	0.260 def	14.11 cde	0.092 bc
Vetch	3.00 d	35.89 ab	0.203 cd	12.15 abc	0.788 c
Sweet Clover	3.20 d	36.91 abc	0.285 efg	11.6 a	0.089 bc
Red Clover	2.83 cd	39.94 e	0.253 cde	14.16 cdef	0.895 bc
White Clover	3.14 d	37.09 bcd	0.393 i	11.82 ab	0.125 a
Mixture	3.00 d	39.82 e	0.326 h	13.58 abcd	0.109 ab
Phacelia	1.95 a	35.58 a	0.146 a	18.45 g	0.075 c
SED	2.224	**0.6698**	**0.03381**	**1.113**	**0.00973**
LSD (P<0.05)	2.434	**1.356**	**0.06845**	**2.254**	**0.0197**

Whole plant quality characteristics more closely represent the interred material from straight sown FBCs (field experiment, chapter 3). The FBCs which successfully overwintered with significantly (P<0.05) higher percentage N in the regenerated material were the perennials, vetch (*V. villosa*) and sweet clover (*M. officinalis*). Carbon levels varied significantly (P<0.05), the greatest levels were demonstrated by crimson clover (*T. incarnatum*), red clover (*T. pratense*), the mixture, black medic (*M. lupulina*) and fallow. Phacelia regenerated from shed seed and demonstrated low levels of N, C and S, however, exhibited a C: N ratio significantly (P<0.05) greater than all other FBCs with the exception of fellow non legume fallow and crimson clover (*T. incarnatum*). Whole plant C: N ratios were below the balance point, with significantly (P<0.05) narrower ratios demonstrated by sweet clover (*M. officinalis*), white clover (*T. repens*) and the mixture. Significantly (P<0.05) higher levels of S were contained within the mixture and white clover (*T. repens*) crops, this is evident by the significantly (P<0.05) narrower N: S ratio.

3.3.15 Soil Analysis

Table 3.26 Autumn 2007 FBCs soil analysis

Autumn 2007 Soil						
FBCs	**% SON**		**% SOC**		**PMN (kg N ha^{-1})**	
Fallow	0.299	b	2.738	abcdefghi	116.11	ab
White Lupin	0.301	b	2.830	efghij	156.39	f
Crimson Clover	0.283	ab	2.662	abcd	132.76	bcde
Black Medic	0.289	ab	2.656	abc	148.30	ef
Vetch	0.289	ab	2.684	abcdef	148.91	ef
Sweet Clover	0.293	ab	2.717	abcdefg	155.23	f
Red Clover	0.286	ab	2.634	ab	126.06	bcd
White Clover	0.292	ab	2.675	abcde	147.69	ef
Mixture	0.302	b	2.735	abcdefgh	96.07	a
Phacelia	0.276	a	2.582	a	118.60	bc
Peas	0.299	b	2.909	j	139.47	def
SED		**0.009**		**0.08**		**10.33**
LSD (P<0.05)		**0.019**		**0.16**		**20.46**

Significant variations were observed within the soil analysis, most pronounced within PMN levels. Significantly (P<0.05) lower levels of SON (%) and SOC (%) was demonstrated by non-legume *Phacelia*. The greatest SOC (%) levels were expressed under white lupin (*L. albus*) and peas (*P. sativum*). PMN levels were significantly (P<0.05) elevated under the annual FBCs black medic (*M. lupulina*), white clover (*T. repens*) and sweet clover (*M. officinalis*). The lowest (P<0.05) PMN levels were under non legume cropping.

Table 3.27 Spring 2008 FBCs soil analysis

Spring 2008 Soil						
FBCs	**% SON**		**% SOC**		**PMN (kg N ha^{-1})**	
Fallow	0.288	abcdef	2.625	abcd	67.36	bcdefgh
White Lupin	0.282	ab	2.595	abc	60.59	abcde
Crimson Clover	0.280	a	2.626	abcd	99.53	j
Black Medic	0.292	abcdefg	2.697	cd	88.43	j
Vetch	0.300	abcdefghi	2.739	d	66.56	bcdef
Sweet Clover	0.293	abcdefgh	2.649	bcd	66.90	bcdefg
Red Clover	0.282	abc	2.554	ab	55.55	ab
White Clover	0.283	abcd	2.514	a	46.35	a
Mixture	0.287	abcde	2.619	abcd	68.31	bcdefghi
Phacelia	0.334	bcdefghij	2.688	cd	57.75	abcd
Peas	0.408	k	2.652	bcd	55.58	abc
SED	**0.02572**		**0.06039**		**10.33**	
LSD (P<0.05)	**0.05155**		**0.121**		**20.46**	

The spring 2008 SON levels varied between the FBCs, with the highest ($P<0.05$) levels demonstrated by peas (*P. sativum*) and *Phacelia.* SOC levels were significantly ($P<0.05$) lower in white clover (*T. repens*), red clover (*T. pratense*), white lupin (*L. albus*), mixture, fallow, and crimson clover (*T. incarnatum*). The highest ($P<0.05$) PMN (kg N ha^{-1}) levels were expressed by crimson clover (*T. incarnatum*) and black medic (*M. lupulina*); the lowest levels were exhibited by grain and forage legumes and non-legume *Phacelia*.

3.4 Discussion

The soil properties in West field were consistent with an arable Sherborne series soil over limestone (Findlay *et al.,* 1984). SOC levels exceed the average levels suggested by Webb et al., (2001), but at 4.2% were consistent with wet – clayey physiotope soils at between 2-5.4% SOC in the UK (Kibblewhite *et al.,* 2007). Soils over limestone posses a high soil pH (7.93 in West Field in May 2007). At these high levels potential interference with Manganese (Mn), Boron (B), Copper (Cu), Zinc (Zn), Iron (Fe) availability may occur. There were no signs of deficiency detected within the trial. Nutrient status (indices 4 and 3 for P and K respectively), indicated sufficient levels for crop growth, although at index 4 there may be some interference with Fe, Cu, Zn availability (DEFRA, 2010).

3.4.1 Botanical Characteristics

FBCs exhibited various botanical characteristics. Annual species *V. villosa* (3.3.5), *P. sativum* (3.3.11) and *L. alba* (3.3.2) produced high levels of biomass (table 3.16) (Fageria, 2007) and are probably most suitable for spring drilling as short term FBCs although exhibiting differing morphology (*L. alba* being an erectile species whereas *V. villosa*, *P. sativum* display a scrambling / sprawling growth habit). Fageria (2007) suggested that FBCs should be relatively economic i.e. utilisation should not incur or induce excessive financial penalties, and identification of species / genotypes to complement the cropping programme is vital (Karlsson-Strese *et al.,* 1998). Erectile species such as *Phacelia*, (3.3.10) *T. incarnatum* (3.3.10), *M. officinalis* (3.3.6), *L. alba* and *T. pratense* (3.3.7) may dominate a companion cash crop, causing reductions in yield through competition for water, nutrients and light as well as harvesting problems (Breland, 1996b). Hence such species are deemed more suitable for straight sowing situations.

V. villosa, *P. sativum* exhibited scrambling growth habits; Briggs (2007) proposed them as suitable for a straight sown scenario. In an undersown (or bi-cropping) situation structural support can be gained from a companion crop, although lodging may be a problem (Cuttle *et al.,* 2003). Compact growth habits and shade tolerance were characteristics exhibited by *T. repens* and *M. lupulina* (Briggs, 2007) and are deemed suitable attributes for an undersown scenario, as well as inducing minimal competition with the main crop, characteristics also mentioned by Cuttle et al., (2003); Broddle (2007) and Breland, (1996b). These species were thought to be less suited to a straight sown environment as they were unable to achieve levels of biomass production comparable to the other test FBCs. Perennial species *T. repens*, *T. pratense* and *M. lupulina* (Table 3.19) displayed excellent over winter capacities, good ground coverage and were considered most suitable for longer term fertility building phases.

3.4.2 Nodulation

Nodulation with *Rhizobium* spp is a key factor in building fertility using legume crops (Fageria, 2007). Assessment of nodule quantity / leghaemoglobin content can provide guidance as to fixation levels (Hardarson and Atkins, 2003). Active nodule counts per plant were similar with the exception of *T. incarnatum* and *M. officinalis* which were significantly higher ($P<0.05$) at 131 and 76.17 respectively / plant (Tables 3.18; Appendix 3.1.4). Inoculation did not induce greater numbers of active nodules compared with the non-inoculated species, although the percentage of nodules displaying inactivity was significantly lower for the inoculated species and for the extensively used temperate legumes *T. repens* and *T. pratense*. Nodule inactivity is an indication either of nodule senescence or of ineffective *Rhizobium* infection. Species demonstrating significantly ($P<0.05$) greater levels of inactivity were *V. villosa; P. sativum* and *T. incarnatum* (11.5; 13.8; 19.8 nodules plant^{-1} respectively) (Tables 3.18; Appendix 3.1.4). *V. villosa* levels were probably in part attributable to this species' susceptibility to cross biovar infection, with less effective strains (Amarger, 2001). Also these species are all denoted as annuals within the UK (Frame, 2005) and the higher levels of senescence may be attributable to life cycle interactions.

Species which did not overwinter were *P. sativum* and *L. alba,* and annuals which did persist were *V. villosa* and *T. incarnatum*. Overwintered FBCs as whole displayed significantly (P<0.05) more nodules in the spring 2008 assessment than in the autumn 2007 harvest (Table 3.19). Perennial forage legumes *T. repens*; *T. pratense*, *M. lupulina* and mixture demonstrated (P<0.05) higher numbers of nodules in spring 2008 than in the autumn 2007 harvest. The 2008 nodule numbers were not significantly different except for *T. pratense* and *M. lupulina* which were statistically (P<0.05) superior in active and non-active nodules respectively compared with all other species. The lowest percentage of inactivity (P<0.05) was displayed by *T. incarnatum*, *M. lupulina*, *V. villosa* and *T. pratense*. (See appendix 3.1.5 and table 3.19)

3.4.3 Biomass yield

Rooting morphology was identified by Thorup – Kristensen *et al.,* (2003) as a key consideration for FBC species selection, comprising approximately half the biomass dependent on species (Breland, 1996B) and therefore contributing significantly to total plant N (Khan *et al.,* 2000; Thorup – Kristensen *et al.,* 2003). Root DM yields in 2007 were not significantly different for all species except *M. officinalis* and *L. alba* which with deep tap root systems were significantly (P<0.05) greater (Table 3.16; Appendix 3.1.4). The non-legume *Phacelia* and fallow treatments, demonstrated extensive root systems which were only out-yielded in biomass by *M. officinalis* and *L. alba*. Over wintered legumes' / non-legumes' below-ground yields (April 2008) were not significantly different except *M. officinalis* which was significantly greater (P<0.01) (Table 3.17; Appendix 3.1.5).

The above-ground performance of an FBC has been highlighted by Cuttle and Goodlass (2004) and Hardarson and Atkins (2003) as an indication of N accumulation and BNF levels, with high biomass production, therefore, as a key criterion for species selection as suggested by Fageria (2007). In the autumn harvest of 2007 highest yielding (P<0.01) species were the grain legumes *L. alba*; *P. sativum* and *V. villosa*. The highest yielding non-legume was *Phacelia*,. This harvest also indicated that the annual and biennial species produced a significantly (P<0.001) greater above-ground biomass than perennial species. By the spring of 2008 the highest yielding annuals had completed their life cycle or over-wintered in poor condition. *Phacelia* shed seeds prior to autumn mulching, and subsequent re-growth occurred both from the original plants and from newly germinated seeds.

In 2008 the lowest yielding perennial species was still *T. repens* (Table 3.17). Highest yielding above-ground production was demonstrated by *M. lupulina* (Table 3.17). *M. officinalis* demonstrated the highest below-ground yield, yet one of the lowest above-ground yields, suggesting that the above-ground growth had not fully commenced in the second year from a crown formation (Frame, 2005).

3.4.4 Chemical composition

3.4.4.1 Nitrogen content

Accumulation of N within the differing species is critical to the pattern / quantities of N release. There was considerable variation between species consistent with Kumar and Goh (2000). *T. repens* and Mixture demonstrated the greatest whole plant N% at 3.2% and 3.1% respectively, and Phacelia the lowest (1.4%) (Table 3.22). In autumn 2007 below-ground biomass N content was significantly (P<0.01) lower in the non-legume~~s~~ species than in the legumes except *L. alba* (Appendix 3.1.6). *T. repens*; *V. villosa*; *P. sativum*; *T. incarnatum* and *M. lupulina* were not significantly different within a range of 1.682-1.975% N. *T. pratense* (2.145%N) and *M. officinalis* (2.404%N) were significantly (P<0.001) greater than these other species. (Tale 3.21; Appendix 3.1.6). Mixtures are suggested by Bergtold *et al.,* (2005) to induce more aggressive competition between species' rooting systems, as they are likely to exploit more of the microbiological profile and thus achieve higher levels of BNF. This was also supported by Høgh-Jensen and Schjoerring (2001) study demonstrating pure stands derived 84% BNF compared with mixtures deriving 92%. Mixtures exhibited the highest below-ground N% expressed by an FBC at 2.506% in 2007 (Table 3.21), and significantly greater than all other species in 2008 and comparable with *M. officinalis* and *T. pratense* (Table 3.24).

In the over-wintered species the lowest N percentages were found in *T. incarnatum*; *M. lupulina* and *T. pratense* which also expressed the highest yield at this time (Table 3.25). All species except *T. incarnatum*, *M. lupulina* and mixture showed higher levels of N within the below-ground root mass. This was most prominent in the non-legume species indicating that over the winter period the species assimilated significant quantities of N in their roots. For example in *Phacelia* N percentage levels rose from 2007 harvest at 0.66% to spring 2008 levels of 1.8% (Table 3.21 and 3.24).

3.4.4.2 Carbon content

There were statistically significant differences between species C levels in roots. The lowest level at both harvests occurred in vetch roots (Table 3.21; 3.24). *Phacelia* contained the highest C content of the non-legume species and was also higher ($P<0.001$) than all the legumes except *M. officinalis* and the mixture. Lower C contents in April 2008 were probably attributable to spring re-growth apart from the perennial species (*T. repens*; *T. pratense*; *M. lupulina*) which demonstrated increased C content compared to the 2007 levels (Table 3.23).

3.4.4.3 Composition interactions

Generally within the roots there was an inverse relationship between C and N. As the C levels increased the N levels decreased. Higher C levels in 2008 compared to 2007 was paralleled with lower N content in 2008 than 2007 (Tables 3.22; 3.25). This indicated progression through root systems' GSs in *M. lupulina*, *T. pratense*, and *T. repens*. The reverse of this was demonstrated in *T. incarnatum*, *V. villosa*, *M. officinalis*, mixture and *Phacelia* probably indicating the production of new rooting material. In *Phacelia* in particular the root material had lower C contents in spring 2008, probably due to the presence of younger plants germinating from shed seeds of the original plants.

There were significant ($P<0.001$) differences in N percentages in shoots harvested in 2007 (Appendix 3.1.6). *Phacelia* demonstrated the lowest percentage (1.4%). The lowest N levels in legumes were in *P. sativum* and *M. lupulina*. Moderate levels were in the range of 2.65-2.84% N expressed by *M. officinalis*; *L. alba*; Fallow; *T. incarnatum*; *V. villosa* (ranked in increasing % order) (Table 3.20). *T. pratense* was superior ($P<0.001$) to all perennial forage legumes except *T. repens* which expressed the highest N percentage (Appendix 3.1.6). The mixture N % was significantly superior to all of its component species except *T. repens*. Within the 2008 harvest the substantial species differentiation had largely been diluted. Non legume species demonstrated the lowest N % levels, however these were not significantly different to *T. incarnatum*; *M. lupulina*; Mixture or *T. pratense.* The highest N yielding species *V. villosa* (3.67%) was also comparable with levels from *M. lupulina*, the mixture, *M officinalis* and *T. repens*.

Carbon percentages within shoots in 2008 followed a similar pattern to the results from autumn 2007 Erectile / semi scrambling crops expressed the highest C % with *M. officinalis* 43.2%; *P. sativum* 43.6% *L. alba* 44.1% *V. villosa* 41.6% each significantly different from each other ($P<0.001$) (Table 3.20, Appendix 3.1.6). The lowest C percentages were expressed by *T. repens* in 2007 and 2008 (34.7 and 37.3%). In April 2008 the C content of all species were not significantly different except *T. repens,* which was significantly ($P<0.01$) lower than all other species. Shoots demonstrated a similar inverse relationship between C and N levels as the roots. Species which exhibited lower N% in 2008 than 2007 also showed higher C%. The treatments exhibiting this trend were the fallow pots, *T. incarnatum, T. repens* and Mixture, indicating that plants were developing and introducing more structural compounds. *M. lupulina*; *V. villosa*; *M. officinalis* however were still in the early stages of development.

3.4.4.4 C:N ratios

C:N ratio is a defining characteristic of species / residue “quality” and potential for degradation (Wedin and Tilman, 1990; Swift *et al.,* 1979), reflecting the previously discussed interactions of botanical characteristics, developmental stage and underpinning residue behaviour once incorporated. Nutrient release or immobilisation of soil N is governed in part by C:N ratio as plant tissue is a primary source and sink for C and N (Fageria, 2007) and has implications on the decomposer community (millipede, fungi and bacterial population) (Elfstrand *et al.,* 2007; Sileshi *et al.,* 2008).

The balance point between residue mineralisation and immobilisation is subject to debate between authors, the general consensus is that high quality / narrow C:N residues release N more rapidly and enhance soil N availability (Snapp and Borden, 2005; Beckie and Brandt, 1997). Cabrera et al., (1994) and Honeycutt, (1999) suggested 20-23 as being the balance point, above 20 leading to slow decomposition (Parr and Papendick, 1978) or induced temporal immobilisation (Doran and Smith, 1991; Rannells and Wagger, 1996; Dinnes *et al.,* 2002).

Whole plant C: N ratios analysis (2007) indicated, the lowest ratio was 11.6:1 exhibited by *T. repens*, significantly lower than all other FBC species. The most significantly different ($P<0.001$) and the only species to exceed the balance point was Phacelia at 28.3:1 (Table 3.22). A more compact distribution of C:N ratios between species occurred in the Spring of 2008 probably attributable to the onset of new growth. The lowest C:N ratios (range of 11.6-14.1) were expressed by *V. villosa*, biennial species (*M. lupulina*; *M. officinalis*), perennial legumes and the mixture (Table 3.22). The greatest C:N ratio was expressed by the non-legume species and *T. incarnatum*, however no FBCs exhibited levels greater than the balance point, suggesting that the majority of N once incorporated would be readily mineralisable.

A study by Snapp and Borden (2005) indicated differentiation between root and shoot components of C:N ratios. Wedin and Tilman (1990) identified below-ground C:N litter quality was highly correlated to N mineralisation rates. In this experiment FBC below-ground material displayed greater variability in C:N ratio than above-ground material. The lowest C:N ratios in 2007 were 15.9-21.6:1 exhibited by the mixture, *M. officinalis*, *T. pratense*, *M. lupulina*, *V. villosa*, *P. sativum*, *T. repens*, and *T. incarnatum* (ranked order) (Table 3.21). Treatment root systems displaying C:N ratios in excess of the balance point were *T. incarnatum*, fallow, *L. alba* and Phacelia at 56.6:1 (Table 3.21). 2008 ratios demonstrated less dramatic variation between C:N ratios of above and below-ground components. All FBCs below-ground material exhibited significantly lower (P<0.001) C: N ratios than *M. lupulina* (Table 3.24).

3.5 Summary of findings

Table 3.28 Summary of pot experiment findings

<table>
<tr><th>FBCs suitability for spring sowing in preparation for autumn cropping.</th><th>FBCs suitability for undersowing prior to autumn cropping.</th><th>FBCs suitability for spring cropping after overwintering.</th></tr>
<tr><td>Botanical characteristics
Rapid growth and assimilation of whole plant biomass and good weed suppression ability are key criteria. The highest (P<0.001) levels were exhibited by L. alba, V. villosa, and P. sativum, and the lowest by Fallow, T. incarnatum, M. lupulina, T. pratense, T. repens and Mixture, suggesting that these species may be less suitable for short duration accumulation phases.</td><td>Key criterion for an undersown FBC is the ability to co-exist with the main crop without negatively affecting main crop performance. Growth habits likely to compete with the main crop are shown by erectile species such as L. alba, T. incarnatum, M. officinalis and scrambling species V. villosa and P. sativum. Lower more prostrate shoot canopies M. lupulina, T. pratense, T. repens are potentially more suitable for an undersown situation.</td><td>Species which overwintered satisfactorily and which would be suitable in an overwintered scenario were fallow, T. incarnatum, M. lupulina, V. villosa, M. officinalis, T. pratense, T. repens, Mixture and Phacelia.

T. incarnatum accumulated the greatest (P<0.001) whole plant biomass.</td></tr>
<tr><td colspan="2">BNF
Successful FBCs will accumulate high levels of N. Assessment of species nodule activities indicated that T. incarnatum, M. lupulina, V. villosa, M. officinalis had the highest (P<0.01) levels of activity compared with the other species</td><td>The greatest (P<0.05) levels of active nodules in overwintered species was demonstrated by T. pratense.</td></tr>
<tr><td>N content – whole plant
The levels of N within an FBC will determine the level available for a following crop. T. repens and Mixture demonstrated the greatest (P<0.001) N% at 3.2% and 3.1% respectively, and Phacelia the lowest (1.4%).</td><td></td><td>All overwintered legume species exhibited similar N%s, except T. incarnatum, Fallow and Phacelia which were significantly (P<0.001) lower.</td></tr>
</table>

FBCs suitability for spring sowing in preparation for autumn cropping.	FBCs suitability for undersowing prior to autumn cropping.	FBCs suitability for spring cropping after overwintering.
N content – below-ground N% levels are lower than those expressed in above-ground material. *Phacelia* expressed the lowest N% at 0.7% whereas *M. officinalis* and Mixture at 2.4 and 2.5% respectively were significantly (P<0.001) greater.	Below-ground material represents the critical N accumulation component for an undersown regime as above-ground material is cut and removed. *M. officinalis* and the Mixture showed the greatest N% in their root systems.	*M. officinalis*, *T. pratense* and Mixture exhibited significantly greater (P<0.05) N% (3.2%; 2.3%; 2.4% respectively) than the other overwintered FBC species.
C:N ratio – whole plant Phacelia had the highest C:N ratio at 28:1, indicating that N in *Phacelia* residue may be prone to immobilisation once incorporated into the soil. The lowest ratio was in *T. repens* (12:1) suggesting rapid N mineralisation.	.	All of the overwintered FBCs expressed a C: N ratio below the “balance point” (20:1) indicating that mineralisation would be likely to occur once incorporated. Fallow, *T. incarnatum* and *Phacelia* expressed the highest ratios (P<0.001) at 18:1; 17:1 and 18:1 respectively.
C:N ratio – below-ground The widest C: N ratio was expressed by non-legumes Fallow (31:1) and *Phacelia* (57:1), however *L. alba*, *T. incarnatum*, *T. repens*, also exceeded the balance point of 20:1, potentially inducing immobilisation when incorporated and delaying the release of nutrition to the following crop.	Below-ground C:N ratio in a under sown scenario can have a pronounced effect. Species with wide C:N ratios, such as non-legumes *Phacelia* and Fallow are likely to induce temporary immobilisation within the soil matrix, potentially limiting or delaying N availability for the succeeding crop.	There were no significant differences between overwintered FBC species with the exception of *M. lupulina* which expressed a C: N ratio of 21:1 which was significantly (P<0.001) higher than the other species.

Chapter 4 – Field Experiment

4.1 Introduction

Economic and political pressures within the UK for greater efficiency in crop production continues to drive the re – examination of crop husbandry approaches and nutrition, and to provide justification for the present investigation. FBCs as nutrient sources offer the potential opportunity to alleviate the economic burden of high fertiliser prices, and to mediate a proportion of losses from arable cropping systems by fixing atmospheric N (legumes) and facilitating the capture of post-harvest available N (non-legumes). Their usage is mainly seen by the agricultural and research communities as being applicable mainly to “organic” systems. However, knowledge transfer to more conventional farming systems and the likely benefits to aid the challenges have not been extensively studied. Cuttle *et al*., (2003) concluded that further research and greater clarity was required accurately to assess N availability from legumes, especially in relation to the nutrition contributions to subsequent crops. The emphasis for this present research therefore, is to refine and utilise some of the knowledge and principles of the use of FBCs in “organic” agriculture and to apply them to a conventional cropping system.

Chapters 2 and 3 have presented introductions to the topic of FBCs and “green manuring” and detail the attributes of the types of FBCs included in this investigation. This chapter contains an account of a field trial which was set up to measure, as accurately as possible, the N contribution of a range of short term legume and non-legume FBCs established under two different cropping regimes, the rationale for their selection and also their effects upon subsequent winter and spring wheat test crops.

4.1.1 Suitability of FBCs

In a field situation Bergtold *et al.,* (2005) highlighted the economic value of high residue "green manure" mixtures, as yields needed to be sufficient to overcome competition (Thorup-kristensen 1993) and to ameliorate soil chemical, physical and biological properties (Fageria, 2007). Yields vary significantly with climatic interactions, soil properties and management practices. Examples of factors causing species yields to vary significantly. include climatic and geographical influences (Laidlaw and Frame, 1988), rainfall and irrigation management (Martiniello, 1999) and the use of an inoculant (Sparrow *et al.,* 1993). Soil (especially pH) variations are important (Sparrow *et al.,* 1993) and FBC species displaying tolerance to alkaline conditions in previous studies include sweet clover (*M. officinalis*) and white lupin (*L. albus*) (Frame, 2005; Soya UK 2007, Azo 2007). This is particularly relevant as the trial site proposed for this investigation has a pH of 7.96 (0-40cm). Below pH 5, white clover (*T repens*) becomes susceptible to Aluminium (Al) and Mn toxicity (Cooper *et al.,* 1983). Furthermore, the associated *Rhizobium* species strain is less abundant and intolerant of acidic conditions which, in part, accounts for reductions in vigour and poor productivity.

Species such as red clover (*T. pratense.*), white clover (*T. repens.*), vetch (*V. villosa*) and crimson clover (*T. incarnatum*) are reckoned to be suitable for a broad range of soil types (Cuttle *et al.,* 2003; Frame, 2005). Soils with high clay content are not thought suitable for crimson clover (*T. incarnatum*) or vetch (*V. villosa* Roth.) and associated problems with poor drainage and waterlogging can hamper the growth of peas (*P. sativum.*), white clover (*T. repens.*) and red clover (*T. pratense.*) (Cuttle *et al.,* 2003; Frame, 2005). The soil on the experimental site, although described as a silty clay loam (See section 4.3.1) is however shallow and relatively well drained (Findlay *et al.,* 1984).

Situations susceptible to drought may perhaps be more appropriate for sweet clover (*M. officinalis*), white lupins (*L. alba*), red clover (*T. pratense.* L) and black medic (*M. lupulina*) as they have tap root systems which tolerate drought more effectively than shallow rooting crops such as white clover (*T. repens.*) (Broddle, 2007; The Organic Research Centre, 2010; Frame, 2005). Vetch (*V. villosa*) is reckoned to be intolerant of drought at the seedling stage, however tolerance increases once the taproot and lateral branch rooting systems are established (Frame, 2005).

High SOM content can cause growth problems for red clover (*T. pratense.*) and white clover (*T. repens.*) (Cuttle *et al.,* 2003). Potentially this derives from the high percentage N assimilated from fixation, which is reduced by the presence of high levels of SMN. Species with high fixation potential tend to be less effective at removing SMN and under high organic matter conditions may be out-competed by N lifter FBCs or superior legumes. Residues from previous sheep grazing an average crop of rape and stubble turnips which occurred on the experimental site during the 2005 / 2006 winter, may influence the outcome of this investigation to some extent.

The majority of FBCs are incorporated into a low N situation post-cereal harvest (Fageria, 2007). Under low N situations N lifters tend to produce lower biomass, lower tissue N concentration (1-2.5%DM) (Martinez and Guiraud. 1990; Anderson and Olsen. 1993) and lower N-uptake (12-31kg ha^{-1} compared with red clover (*T. pratense* 44 and 98 kg ha^{-1}) (Vyn *et al*., 2000). This effect is attributed to lower N availability and the plant's N acquisition mechanisms (Francis. 1995; Thorup-Kristensen. 1994b; 2001).

Thorup-Kristensen. (2001) and Torbet *et al*., (1996) found little or no differences between legumes and non-legumes when green manuring took place on soil with a high mineral N content. However Hardarson and Atkins (2003) showed that high N levels influence the infection, development, and senescence rates of nodules; basically as soil N level increases the activity of the symbiosis declines. This was attributed to the legumes' preferential uptake of readily available N rather than obtaining it via fixation (Hardarson and Atkins, 2003). The extent to which soil N levels influence BNF is species dependent. For example *Lupinus* spp., peas (*P. sativum*) and *Faba* beans will maintain high rates of BNF (approximately 90%), whereas soyabean *Glycine max* [L] Merr. was demonstrated to be susceptible to high soil N (Hardarson *et al.,* 1991; Richards and Soper, 1979) or the use of inorganic N fertilisers (Sawyer, 2006).

Generally legumes are considered to be less effective at accessing and depleting SMN than non-legumes (Vyn *et al*., 2000). Breland. (1996a) added 40kg N ha^{-1} to two clover species. They were unable to access and deplete the addition whereas perennial ryegrass (*Lolium perenne.* L) removed it within one week. This knowledge is particularly important if considering the usage of different FBCs species to reduce nitrate leaching.

4.1.2 The importance of residue quality

Section 2.3 deals extensively with the topics of residue quality and the underlying mechanisms governing the mineralisation of N. In general the concentration of N in residues is an important predictor of N mineralisation. Vahdat *et al.,* (2011) found that N concentration was significantly correlated to mineralisation (R^2=0.969). However, Vahdat *et al.,* (2011) also indicates the need for knowledge of biochemical quality as a predicative tool. Chemical composition of residues varies between species, age and management techniques (Flower *et al.,* 2012). The most extensively used index for describing residue quality is C:N ratio (Vahdat *et al.,* 2011; Cochran *et al*., 1980; Kuo and Jellum. 2000). It is defined as the ratio of the mass organic C to the mass of organic N in the soil, organic matter, plants or microbial cells (Soil Science of America 1997). Generally plant C content ranges from 40-50%, whereas N content varies more significantly (Kumar and Goh, 2000). The C:N ratio performs an important role in the release or immobilisation of soil N because plant tissue is a primary source of C and N (Fageria. 2007) and hence a useful mechanism for predicting residue behaviour within the soil (Chaves *et al.,* 2004), as evidenced by the Kumar and Goh (2002) study where 71% of the variation in grain yield was accounted for by the C:N ratio of residues.

Generally, residues with a low N or high C:N have slow decomposition rates indicating N immobilisation within the early stages of decomposition (Parr and Papendick, 1978; Mohanty *et al.,* 2011; Verhulst *et al.,* 2011). Cereals tend to possess higher C:N ratios in comparison with legumes (Fageria. 2007; Mohanty *et al.,* 2011). Narrow or low C:N ratios tend to enhance soil N availability, whereby 50% of plant mineral N becomes available within two weeks of incorporation (Mastrop and Kirchmann, 1991; Beckie and Brandt, 1997; Beckie *et al*., 1997; Bergkvist *et al.,* 2011). The majority of FBCs have C:N ratios of 10 - 30 (Thorup-Kristensen *et al.,* 2003; Janzen and Kucey, 1988).

Thorup-Kristensen (1994b) indicated legumes in general have a positive influence on N supply for following crops, whereas N supply post non-legume FBCs is more uncertain. Kumar and Goh (2002) and Lupwayi *et al.,* (2006) studies reported significant correlations between C:N ratio and residue release. The balance point between mineralisation and immobilisation turnover (MIT) within the soil is subject to debate. Variability in early responses to FBC incorporation is largely attributed to species residue quality and its influence on the MIT balance point (Francis et al., 1998; Clement et al., 1998). Mastrop and Kirchmann, (1991); Thorup-Kristensen (1994a) and Gilmour (1998) concluded that it occurred at a C:N ratio of 15, whereas St. Luce *et al.,* (2011), Tejada *et al.,* (2008) and Frankenberger and Abdekmagid (1985) found that 20 was the balance point. However, Doran and Smith (1991); Green and Blackmer (1995); Ranells and Wagger (1996); Dinnes *et al*., (2002) indicated that a C:N ratio of <20 induced temporary (two weeks) immobilisation.

Although C:N is the most extensively utilised index for residue quality, several studies have highlighted problems with its utilisation as an indicator of N mineralisation (Collins *et al*., 1990). Vigil and Kissel (1995) concluded that it estimates N mineralisation parameters poorly, especially in the C:N range of

10-28. This is particularly critical since this range encompasses the MIT balance point. Ruffo and Bollero (2003) concluded that the availability of *soluble* C and N rather than their concentration in residues plays a more critical role in decomposition and nutrient release. Studies observing how soluble C affects the rate of N mineralization were reported by Kuo and Sainju (1998) Magid *et al*. (1997). Soluble fractions are easily decomposable and rapidly released (Qafoku *et al.,* 2001). Many FBCs have relatively high levels of soluble N as nitrate (0-<2.5%) and are highly susceptible to losses (Lainé *et al*., 1993; Thorup-kristensen 1994a). Lupwayi *et al.,* (2006) found nutrient release was correlated with microbial activity and Mastrop and Kirchmann, (1991) indicated that increases in microbial populations such as under field conditions may induce further mineralization of more recalcitrant residues. Neergaard *et al*., (2002) under field specific conditions found that even insoluble fractions were also decomposed.

Other residue quality parameters can have a bearing on N release and are often considered to be more closely related to residue decomposition. These focus on the structural components and physiological changes that occur during plant growth and development. Such parameters include cellulose content (Bending *et al*., 1998); lignin content (Mueller *et al*., 1988; Flavel and Murphy, 2006; Vahdat *et al.,* 2011) and ratios such as lignin (L) to N (L:N) (Vigil and Kissel. 1991; Flavel and Murphy, 2006) and polyphenol and lignin to nitrogen (P/L/N) (Constantinides and Fownes. 1994; Melillo *et al.,* 1982; Pastor and Post, 1986; Seneviratne, 2000). Becker *et al*., (1994) identified L:N ratio as a significant factor in controlling N release. Vahdat *et al.,* (2011), Lupwayi *et al.,* (2006) and Srinivas *et al.,* (2006) studies agreed and found a significant correlation between N release and L:N and lignin. However, the nature of annual FBCs means that they tend to be young plants and structural changes via lignification are generally associated with mature crops (Fox *et al*., 1990). This is likely to mean FBCs will be consistent with the Fox *et al*., (1990) and Hatch *et al*., (1994) findings where greater N mineralisation took place under legumes or grass/legume mixtures, attributable to easily decomposable material, low C:N ratios and other quality parameters, e.g. low L : N ratio, low P/L/N ratio and higher litter contribution from legumes compared with grasses (Gil and Fick. 2001). Where the morphology between species is diverse other physiological characteristics may also influence decomposition rate.

To summarize, the C:N ratio provides a general description of residue behaviour in decomposition. More specific interpretation is via lignin to N and lignin to polyphenol to N ratios. However the early stages of mineralisation are largely dependent on the size of the water soluble C pool and an intermediately available C pool (Reinertsen *et al*., 1984; Gilmour, 1998).

4.1.3 Wheat N requirement

Nitrogen is an essential plant nutrient at the centre of plant metabolism (Kirkby *et al.,* 2009). Crops such as winter wheat are highly responsive to N inputs (Dampney *et al.,* 2002) and it is a controlling factor on crop development and yield in temperate Europe, as water is not usually a limiting factor to photosynthesis (Olesen *et al.,* 2002). The key variables for determining N efficiency in wheat are, grain yield, together with total N uptake and N harvest index (Barraclough *et al.,* 2010). Generally wheat has a lower NUE compared to other cereals such as barley. For example Delogu *et al.,* (1998) reported barley N recovery levels at 63% whereas wheat was 49%. Dampney *et al.,* (2006) also reported significant differences in N requirements and cultivars' ability to partition and scavenge soil N.

The main parameters of quality grain are nutritional and dough characteristics, which are as a result of the translation of N to grain protein (Jie *et al.,* 2006). Grain protein is governed by a source – sink relationship whereby grain demand varies largely as a response to total N content in the crop (source determined) rather than to the grain number (sink determined) (Jamieson and Semenov, 2000). Vegetative accumulation (source) is a product of canopy expansion, light interception, radiation use efficiency and is also affected by temperature and water supply (Jie *et al.,* 2006; Olesen *et al.,* 2002; Sylvester-Bradley *et al.,* 1997) and management i.e. cultivar selection and population density (HGCA, 2000). These factors directly feed into grain N via postanthesis remobilisation of nutrients (Jie *et al.,* 2006; Delogu *et al.,* 1998), evidenced by the decline in N% as the plant develops (Greenwood *et al.,* 1990). Sylvester-Bradley *et al.,* (1997) and HGCA (2000) have presented studies on the canopy size to gain maximum light interception. These concluded that the optimum green leaf area index (GAI) i.e. the units of green surface / area of ground is between 5.2 (Sylvester-Bradley *et al.,* 1997) and 6 (HGCA, 2000).

In order for crops to reach their target GAI, yield and quality targets they require regular pulses of N (Tonitto *et al.,* 2006). HGCA / RB209 guidelines indicate N is required at stem extension through to flag leaf emergence. Petersen's (2004) ^{15}N crop recovery study indicated an increase in recovery by 0.47% point / day^{-1} when fertiliser application was postponed from tillering until second node detectable at stem extension (GS 32) (Petersen, 2004), but a decrease by 0.19% point / day^{-1} from flag leaf sheath opening (GS 47) to maturity (GS 85-87) (Petersen, 2004).

Tonitto *et al.,* (2006) indicated that cereal yield response was correlated to legume FBC biomass production. Poor biomass production may be a response to inappropriate management or the morphology of specific species (Flower *et al.,* 2012). The influence of a range of FBC species on the yield of subsequent crop was demonstrated by Stopes *et al.,* (1996). Growing red clover (*T. pratense.*); white clover (*T. repens.*); black medic (*M. lupulina* L) and ryegrass (*L. perenne*) resulted in winter wheat yields of 6, 5.2, 3.3, and 2.1t ha^{-1} respectively, compared to a control with no green manure yielding 4.8 t ha^{-1}. This study concluded that winter wheat (*T. aestivum*) yield was greater following legume green manuring than following ryegrass. Furthermore it was also concluded that a 1 year red clover or white clover green manure was sufficient to increase yield, and produce a higher grain N content in a following winter wheat crop (Stopes *et al.,* 1996). However neither black medic (*M. lupulina* L) nor ryegrass (*L. perenne*.) accumulated sufficient N to allow net mineralization at a rate able to meet the full N demand of a commercially viable crop of quality wheat, presumably attributed to residue immobilisation or pre-emptive competition (Stopes *et al.,* 1996) or simply to insufficient BNF. This experiment demonstrated a treatment species correlation with yield but with no other parameters including specific weight; grain size; P or K content (Stopes *et al.,* 1996).

It appears important to try to match residue release patterns to crop uptake to maximise subsequent crop yield and thus to optimise the response from inorganic fertilisers (Chirinda *et al.,* 2010). Sarrantonio, (1991); Holderbaum *et al*., (1990) and Decker *et al*., (1994) all indicate the importance of identifying optimal legume or other FBC and cash crop combinations.

4.2 Experimental Aims

The aim of this experiment was to investigate, and accurately to measure, using a field trial, the N contribution of a range of short term legume and non-legume FBCs and establishment methods, and their effects upon subsequent winter and spring wheat test crops.

4.3 Materials and Methods

The selection of leguminous and non-leguminous FBCs established by straight sowing or under-sowing were grown for between 6 weeks and 10 months and the resulting fertility assessed using winter and spring wheat test crops, in a field trial. The trial was initiated in February 2007 near Cirencester and concluded in August 2008. The FBC species were assessed and analysed throughout their growth periods and their influences on the growth and performance of succeeding wheat test crops was monitored. In addition soil biochemical characteristics were monitored to aid understanding of residue release patterns and test crop behaviour.

The FBCs investigated in this field trial have also been subject to detailed examination using a pot experiment (see chapter three) where they were grown in soil taken from the experimental site. Information from the pot trial particularly the below ground data will be used further to inform the discussions of results from this trial and the modelling in chapter five. Ideally the pot trial would have been completed in advance of the field trial but time constraints did not allow this.

4.3.1 Experimental Site

The experimental site was selected and the field trial initiated in February 2007, in West field on the RAC's Coates Manor Farm, Cirencester UK (OS grid reference SO 984004). The trial was established on a gentle south west facing slope, away from the headlands and abnormal field features (see plate 4.1). The soil series was Sherborne series Cotswold Brash over Oolitic limestone (Findlay *et al.,* 1984). Mechanical analysis of soil samples gave the texture at the site as silty clay loam. The rest of the field was sown to spring beans (*V. faba*) cv. Fuego in February 2007 and, in the autumn of 2007 with winter wheat (*T. aestivum*) cv. Claire. Spring Barley (*Hordeum sativum*) cv. Cocktail was sown in the relevant parts of the experimental area on 13th April 2007 and the FBCs then either undersown or straight sown using C1 generation seed on the 24th April – 5th May 2007 and again, after spring barley harvest, on the 22nd - 24th September 2007 according to the requirements of the experimental design (see plates 4.1 and 4.3). The spring barley was combined on 17th August 2007 using a Sampo trial plot combine harvester and the straw baled and removed, before establishment of the winter or spring wheat test crops.

4.3.2 Experimental design

The treatments were arranged in a randomised block design with split plots and sub-plots. Winter or spring wheat test crops were the main plots and cropping regimes and FBCs the split plots and sub-plots. The complete layout and randomisation of treatments is shown in table 4.1

Plate 4.1 Field trial location in West Field - SW aspect. - May 2007

4.3.3 Treatments

All FBC treatments were examined under each of three cropping regimes and using two test crops as set out in table 4.1.

4.3.3.1 FBC treatment details

The following species and cultivars were established with C1 generation seed on the 5th-7th June 2007:

1. Natural regeneration fallow (weeds and volunteer crop plants allowed to germinate and establish freely)
2. *L. albus.* white lupin cv. Dieta "Lupigen" (Soya UK Ltd.)
3. *T. incarnatum*

, crimson clover cv. Contea

4. *M. lupulina*. black medic cv. Virgo Pajberg
5. *V. villosa*. hairy vetch cv. Nitra
6. *M. officinalis*. yellow sweet clover, commercial seed not certified as to variety.
7. *T. pratense*. red clover cv. Milvus
8. *T. repens.* white clover cv. Aberherald

9. A mixture of legumes (*T. pratense*. cv Milvus 40% inclusion, *M. officinalis*. cv [not specified], 30% inclusion, *T. repens.* cv. Aberherald, 15% inclusion and *M. lupulina*. cv. Virgo Pajberg 15% inclusion.
10. *Phacelia*. cv. Balo
11. *P. sativum*. field peas cv. Cooper

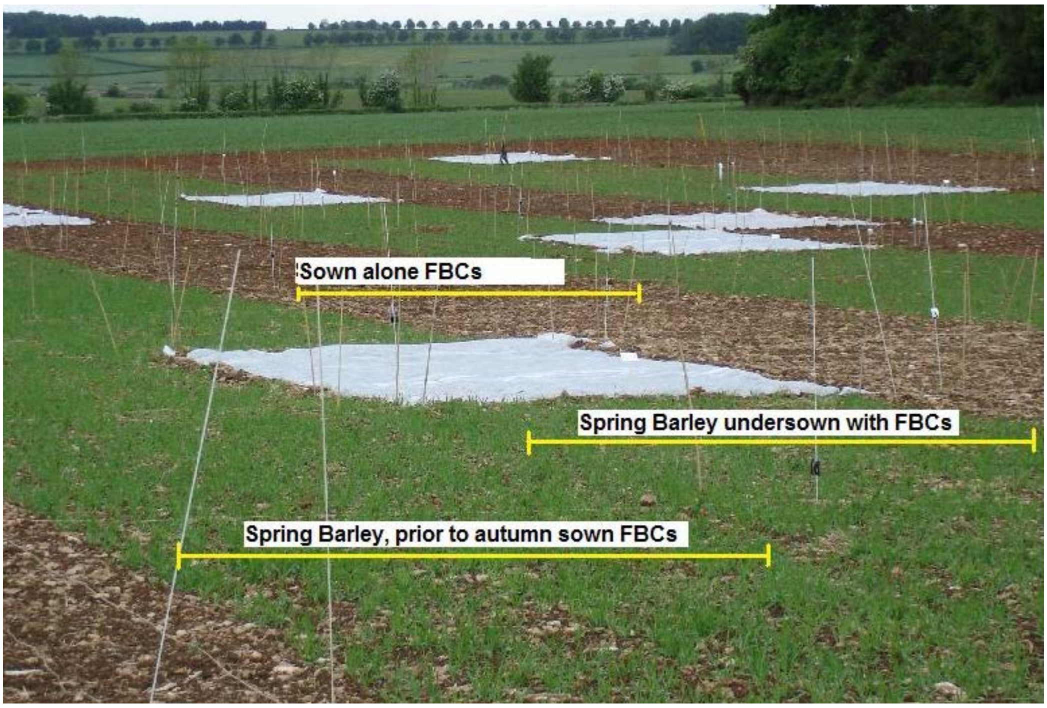


Plate 4.2 A photograph of West field experiment showing main plots overlaid with split plot treatments – May 2007

Natural fallow regeneration within this experimental design is designated as a treatment in the sowing regimes. “Straight sown” fallow did not in fact involve any seed sowing but merely allowed weeds and volunteer crop plants to grow naturally between April and September 2007 and constituted a “do nothing” control to set against the 10 other straight sown FBCs. (“Straight sown” fallow was also included as a treatment in the pot experiment). Similarly, regarding the “undersown fallow”, no seed sowing took place and this treatment was in effect non-undersown spring barley. However, the nomenclature of “straight sown” and “undersown” for these treatments has been retained in the interest of consistency.

Table 4.1 Layout and randomisation of treatments for short term FBC trial, West field, Coates Manor Farm.

Replicate	BLOCK I						BLOCK 2						BLOCK 3					
Test Crop (main plots)	Winter wheat 2007			Spring wheat 2008			Winter wheat 2007			Spring wheat 2008			Winter wheat 2007			Spring wheat 2008		
Cropping regime (split plots)	SS Spr	US Spr	SS Aut	SS Spr	US Spr	SS Aut	SS Spr	US Spr	SS Aut	SS Spr	US Spr	SS Aut	SS Spr	US Spr	SS Aut	SS Spr	US Spr	SS Aut
FBC Treatments (sub-plots)	2	8	1	11	9	5	6	3	8	10	2	7	10	5	2	4	3	8
	1	3	4	6	4	7	4	10	9	5	4	1	7	9	11	1	9	10
	11	4	10	1	6	8	3	11	5	7	9	2	2	7	8	7	8	6
	7	9	9	7	1	11	9	6	2	4	10	4	5	1	10	8	10	3
	10	6	11	9	5	2	1	1	11	3	7	6	8	2	3	2	4	11
	5	10	7	3	11	10	10	4	6	1	11	8	4	10	6	11	5	2
	3	7	1	2	8	3	8	9	1	6	5	10	9	3	5	9	7	1
	4	11	5	8	3	6	11	5	4	2	3	11	1	8	1	6	11	4
	9	5	3	10	2	1	2	7	10	8	1	9	3	6	4	10	2	7
	8	1	6	4	10	9	5	8	7	11	8	3	11	11	7	3	1	9
	6	2	8	5	7	4	7	2	3	9	6	5	6	4	9	5	6	5

FBC treatments

1	Fallow
2	Bitter Lupin
3	Crimson Clover
4	Black Medic
5	Winter Vetch
6	Sweet Clover
7	Red Clover
8	White Clover
9	Phacelia
10	Mixture 40% Red clover 30% Sweet clover 15% Black Medic 15% White clover
11	Peas

Cropping regimes

SS Spr = Straight sown in April

US Spr = Undersown in spring barley cv. Cocktail in April

SS Aut = Straight sown in August after spring barley harvest

Test Crops

Winter wheat cv. Claire sown in October 2007 for combining August 2008

Spring wheat cv. Ashby sown in April 2008 for combining August 2008

Trial dimensions

Trial width 63m x 96m deep

Sub plots 6m x 3m to be combined with TAG 2.4 m plot combine

4.3.4 Conduct of the trial

4.3.4.1 Preparation

Site preparation commenced 14th February 2007 with the preliminary demarcation. The trial area was fully marked out on the 20th April 2007. Trial location measures were also implemented, including permanent markers installed in the field boundaries, in conjunction with buried magnets to denote the trial corners.

Soil samples were collected with a Dutch auger to 30cm from 5 random positions within each of the sub-plots. The samples were bulked, sub sampled and analysed for soil texture, pH, SON, soil P, soil K and SOC to provide baseline data. Details of the entire laboratory methods employed are given at appendix 1.3.

Soil analysis using the PMN technique (Antil *et al*., 2001) required confined sampling areas to be established to reduce spatial plot variation and to give an accurate representation of soil mineralisation activity. Four small canes were inserted in random locations within the plot to give an area 0.5 m^2 from which mineralisation samples were subsequently taken (see plate 4.3).

Plate 4.3 Example of a mineralisation sampling area

4.3.4.2 Establishment

4.3.4.2.1 Accumulation phase

The trial area was cultivated twice with a Väderstad Topdown cultivator in early April 2007. Spring barley (*H. sativum*) cv. Cocktail was drilled with a Horsch 6m drill on the 13th April 2007 at a seed rate of 150kg ha^{-1}. Once the barley emerged on 20th April 2007, individual sub-plot demarcation and the establishment of the FBCs commenced.

Sowing the seeds of the various FBCs commenced on the 25th April and concluded on the 2nd May 2007. Autumn cultivations for the establishment of autumn sown FBCs occurred on the 21st September 2007 with a Kuhn 3m power harrow, and sowing took place between the 22nd - 24th September 2007. FBC seeding rates for both spring and autumn sowing are given in table 4.2. These seeding rates were decided upon having regards to approximate seed size and what would be considered “normal” commercial rates, in order to achieve good crop stands (Cuttle *et al.,* 2003; Wilkinson, Cotswold Seeds Ltd; McNaughton, Soya UK. Pers. Comms;).

Table 4.2 FBCs seed rates

FBC species	Seed rate (kg ha^{-1})
Lupin	175
Crimson clover	15
Black medic	7.5
Vetch	100
Sweet clover	15
Red clover	15
White clover	7.5
Mixture (pre mixed by Cotswold seeds Ltd)	15
Phacelia	10
Peas	228

Legume FBCs for successful fixation require species specific *Rhizobium* association (Amarger, 2001). The experimental site cropping history and expert advice was sought (Wilkinson, Cotswold Seeds Ltd and McNaughton, Soya UK. Pers. Comms) to inform which species were likely to require a different strain of *Rhizobium* to the native population for effective nodulation. FBCs which received a host-specific strain at sowing in the form of an inoculant (Legumefix, Legume Technology Ltd.) were white lupin (*L. albus*) with *Bradyrhizobium lupinii*; black medic (*M. lupulina*.) and sweet clover (*M. officinalis*) with *Siniorhizobium meliloti.* Inoculants were mixed thoroughly with the seeds according to suppliers instructions, latex gloves were worn whilst handling inoculated seed and disposed of between inoculants to reduce potential cross-contamination.

Sub-plot boundaries for sowing purposes were marked with twine. The seed for each sub-plot was weighed (±0.01g), and then bulked in the field with 2kg of sharp sand and hand sown. Seeds such as peas and lupins requiring an optimum sowing depth of 2.5-5cm (Crowley, 1998) were established by hoeing out drills 15-20cm apart and hand sowing seed into the rows before raking over. All other seed (and fallow plots) was suitable for broadcasting and hand raked in two directions to provide a sowing depth of 10-20mm. All FBC sub-plots were rolled with a Cambridge roller after sowing, to provide a consolidated level seedbed and to maximise seed/soil contact.

4.3.4.2.2 Test cropping phase

Autumn cultivations prior to the establishment of winter wheat cv. Claire in the relevant main plots, occurred on the 26th of September 2007 with two passes of a Kuhn 3m power harrow. The crops were established with a 6m Horsch drill on the 27th September at a seed rate of 300 seeds m^{-2}. Main plots which had been drilled were rolled with a Cambridge roller. Spring cultivations commenced 19th February 2008 and the spring wheat test crops were established by the same method. Spring wheat cv. Ashby was sown at a rate of 420 seeds m^{-2} on the 27th March 2008.

4.3.4.3 Crop management

4.3.4.3.1 Accumulation phase

Double electric fences were established around the entire perimeter of the trial to minimise rabbit (*Oryctolagus cuniculus*) damage. The fencing system was installed by 27th April 2007 and maintained live throughout the duration of the field trial (see plate 3.5. A protective layer of agricultural fleece was installed on the pea and lupin sub-plots to minimise damage from pheasants (*Phasianus colchicus*) and pigeons (*Columba* spp.). Fleece was cut ½ m larger than the sub-plot dimensions and the edges buried into the guard strips (see Plate 4.6). Fleece was installed the 4th May 2007 and removed on the 2nd June 2007, once the plants were well established. To protect the trial further from bird damage, bird scaring devices (serrated black bin bags) on long canes were also distributed across the trial area.

Plate 4.4 and 4.5 Photographs demonstrating the pest protection methods used in the West field trial - May – June 2007.

Plate 4.4

Plate 4.5

No herbicides or fungicides were applied to the trial area during this phase, since no one product could universally be applied to all the FBCs. The spring straight sown FBCs were mulched using a BCS mower on the 17th August 2007. Plants were cut to about 5cm stubble and all material was returned to the plots. The undersown and non-undersown spring barley split plots were combined 17th August 2007 using a Sampo 2.15m cut plot combine. The straw was subsequently swathed, baled and removed. Budgetary constraints precluded the individual recording of spring barley grain yields relevant to specific FBC treatments.

4.3.4.3.2 Test cropping phase

Winter wheat test crops received slug pellets (Draza Forte [Bayer Crop Science] - active ingredient methiocarb) applied on the 20th of October 2007 at a rate of 3.75kg ha^{-1} after the observation of low level damage. Herbicides (see Appendix 2.5) were applied when the weed levels were considered detrimental to the trial outcome, crops were sprayed either with a Honda quad bike fitted with a 2m boom, or a Hardi knapsack sprayer fitted with a 1m hand held fan nozzle. Fungicides and plant growth regulators were applied to both the winter and spring wheat test crops at the same time, and using the same machinery as the surrounding commercial farm wheat crop. Discard areas within the trial area had been designated as tramlines and a Honda sprayer was used to make the applications indicated in appendix 2.5.

4.3.4.4 Sampling and Harvesting

4.3.4.4.1 Accumulation phase vegetation sampling

Plant population counts were undertaken on the 6th-16th July 2007 by random quadrat analyses replicated three times across the plot using a 0.25m^2 quadrat. The overwintered treatments were not assessed by plant population counts since individual plants were mostly impossible to differentiate due to the stoloniferous growth habits of some species.

Individual plot assessment of the percentage ground cover of FBC species and weed species identification and percentage ground cover were also carried out. Levels were assessed by replicated (3 times) random 0.25m^2 quadrats. Supportive photographic evidence was also collated. The assessments took place on the 18-24th July 2007. Above-ground biomass material was harvested 29th July – 8th August 2007 with secateurs to within 3-5cm of the ground using two randomly allocated quadrats (0.25 m^2) per plot. Material was bagged and labelled and transported rapidly to the laboratory fridges or cold storage to limit crop transpiration and respiration before processing. Below ground data was not attempted due to the practical difficulties of extraction of root material in the field. It was decided instead to utilise the results gained from the pot experiment (chapter three) where identical FBCs were grown in soil taken from the experimental site.

4.3.4.4.2 Test crop vegetation sampling

Winter wheat data collection included population counts plants m^{-2}(assessed on the 6th February 2008) and ears m^{-2} (assessed on the 15-16 of July 2008). Both counts used randomly allocated replicated (3 times) quadrats ($0.0625m^2$) across the plot. Assessment of the number of tillers per plant occurred on the 14th April 2008, 6 plants were randomly selected within each plot and the numbers recorded.

Winter wheat crops green leaf area (GAI or green area index) was assessed using a Sun Scan device, (Delta T Devices Ltd, Cambridge). Four randomly situated readings were taken per sub-plot. An assessment was made at stem extension (GS 32, 5th-6th May 2008).

Above ground biomass material was harvested using the same procedure as the accumulation phase vegetation. The winter wheat test crop was sampled four times over the crop's development whereas the spring wheat test crop was only sampled at soft dough harvest. The timings and descriptions of vegetation harvests are detailed below.

Table 4.3 Test crop vegetation recovery harvest programme for 2008

Date	Description	Crop GS
14/02/08	Winter Wheat tillering harvest Row 1 – previously straight sown FBCs	23
18/02/08	Winter Wheat tillering harvest Row 2 – previously undersown FBCs	23
6/05/08	Winter Wheat stem extension harvest Row 1 – previously straight sown FBCs	32
7/05/08	Winter Wheat stem extension harvest Row 2 – previously undersown FBCs	32
29/5/08	Winter Wheat flag leaf emergence harvest	39 – 45
14/7/08	Winter Wheat soft dough harvest	85
12/8/08	Spring Wheat soft dough harvest	85

Plots were combined on the 26th August 2008 with a Sampo (2.15 m header) trial plot combine, on-board moisture and yield readings were taken from each plot. A grain sample from each plot was collected to undergo further analysis within the laboratory.

4.3.4.4.3 Soil sampling in accumulation phase

Stone content across the trial site was assessed by photographic evidence of the soil and visible stone content, taken from random locations. From these sites 15kg (±-0.1kg) of soil was extracted and the sample separated into stone and soil content and weighed.

SON and SOC for each plot were assessed at the commencement of FBC establishment (previously discussed) and at the conclusion of the accumulation phase. Each plot was cored with a Dutch auger 3 times to 30cm deep, hand crumbled and sub-sampled. Samples were placed in sealable labelled bags, transferred rapidly to the laboratory, kept below 4ºC and initial processing occurred within 12 hours of sampling. Sampling occurred on the 22 and 26th November 2007 for winter wheat test crop and the 19th February 2008 pre-entry for the spring wheat test crop.

4.3.4.4.4 Soil sampling in test cropping phase

Mineral N repeatability analysis of the field trial indicated that sample results were significantly influenced by delays (<24hrs) in analysis after coring (Appendix 1.4). Therefore a stipulation was put on N sampling, that initial processing had to occur within 12 hours of sampling.

SON and SOC measurements were taken from each plot at the end of the test cropping phases. The sampling procedures were the same as previously discussed. Plots were sampled on the 27th and 28th August 2008 post winter wheat and spring wheat test crop harvests.

Soil PMN, comprised two main components; initial mineral N figures were measured on the day of coring and secondary N analysis took place post-incubation (i.e. creation of an ideal situation). Monthly sampling took place within a 1x0.5m² area (see plate3.3). Sampling was undertaken with a narrow gauge corer to 30cm, replicated 6 times and sub-sampled. Monthly sampling of sub-plots occurred over 2 days to enable all samples to be processed within 12hrs.

4.3.5 Laboratory Assessments and Analyses

4.3.5.1 Plant tissue analyses

Material from each replicate of each plot was sorted into FBC species; barley if under sown and admixture (weeds, plus any other material). Mixtures were segregated into each FBC species. The FWs of each plot component were recorded, dried at 100ºC for 24hrs and then the dry weight recorded to give species components DM yield.

Nitrogen content in the roots and shoots as well as residue quality (C: N ratio) were analysed via an Elementar Cube CNS auto analyser. Plant tissue samples were dried. The samples were coarse milled (0.05mm gauze), then sub sampled and further micro-milled to obtain a finely divided sample with a narrow particle size distribution. 25mg (± 0.05 mg) of well mixed samples plus equal weights of Tungsten oxide were weighed on a five place analytical balance into aluminium or zinc foils. Encapsulated samples were then analysed on the auto analyser. (For full details see appendix 1.2).

Grain quality measures including thousand grain weight, specific weight, admixture screening (above and below 2mm) and crude protein percentage were all assessed, the latter by the CNS method. In addition a detailed grain analysis of all winter wheat samples from block 1, sown alone and undersown with FBCs was undertaken. This detailed analysis comprised of weighing 50g (±0.01) of randomly selected sample and assessing for admixture, broken, shrivelled, sprouted and fusarium infected grain and chaff. The exact weights of each component were recorded.

4.3.5.2 Soil analyses

The soil samples obtained from each plot were assessed for SON and SOC on the Elementar Cube CNS auto analyser methodology as previously described (for full details see appendix 1.3) and for PMN (see appendix 1.3)

Soil PMN measurements were taken at the commencement and conclusion of the accumulation phase and monthly sampling of winter wheat in the test cropping phase. This technique required soil mineral N measurement, DM analysis and anaerobic incubation measurement (for full details see appendices 1.3). Samples were passed through a 6.7mm sieve, and any visible plant material was removed. 50g (± 0.05g) of fresh soil was oven dried at 100ºC for 24hrs for DM analysis to adjust the N figures. Analytical replicates of each sample were then weighed 25g (± 0.02g) into extraction bottles, with 100ml of 0.5*M* K_2SO_4. Samples were shaken and filtered through Whatman GFA 40 filter papers and the extracts then frozen in preparation for NH_4 and NO_3 analysis on FIA. Potential mineralisation rates were determined by an anaerobic incubation method (Antil *et al.,* 2001 Lober and Reeder. 1993) (See appendix 1.3)

4.3.6 Statistical Analysis

Data was subjected to statistical analysis by means of Genstat 12th Edition (VSNi Ltd). Differences between treatments were established using various ANOVA and Regression techniques.

4.4 Results

4.4.1 Performance of FBCs

4.4.1.1 Establishment data

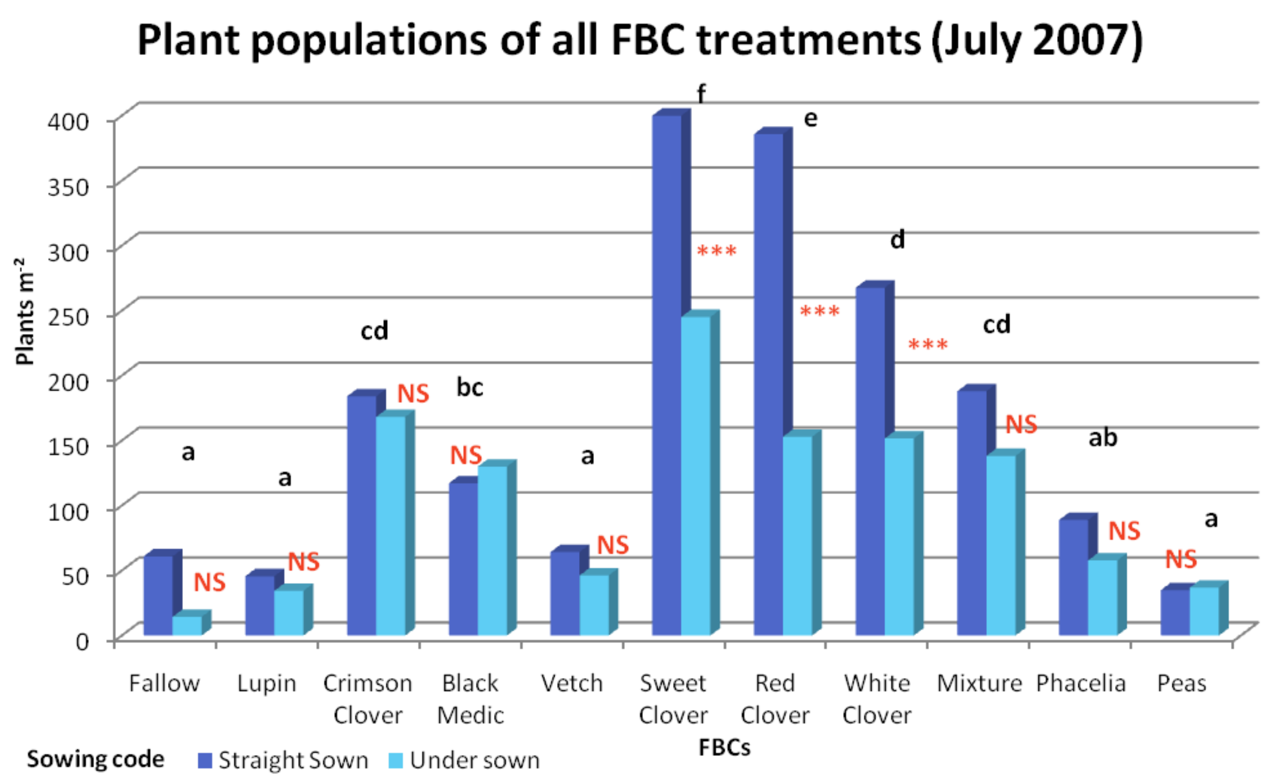


Figure 4.1 FBC plant populations metre^{-2}.
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Pairs of bars with the same letter are not significantly different ($P<0.05$). Pairs of bars labelled *** ($P<0.001$) or NS indicates significance of the interaction between sowing code and species plant population.

Plant Population	M.S	df	P value
Species	359424.0	10	<0.001
Sowing code	357601.0	1	<0.001
Species x Sowing code	52578.0	10	<0.001
Residual	13092	372	

The same sowing rates were used for both establishment methods (sowing codes). Significantly ($P<0.001$) lower populations were recorded in undersown treatments compared to straight sown (average 106.9 v 167.0 plants m^{-2} respectively. Plant populations of sweet clover (*M. officinalis),* red clover (*T. pratense*) and white clover (*T. repens),* were all significantly ($P<0.001$) reduced by undersowing.

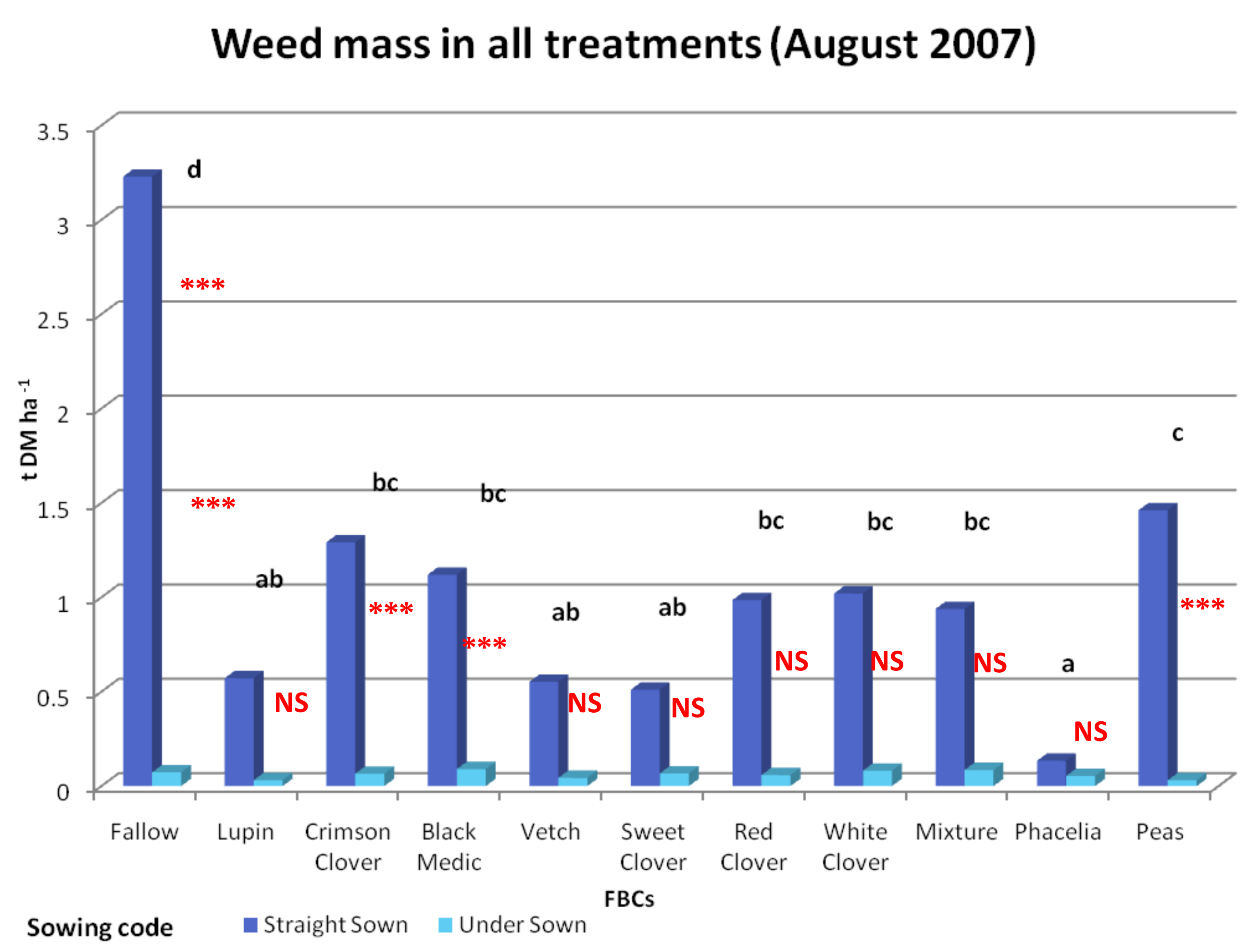


Figure 4.2 FBC weed mass

Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Single bars and pairs of bars with the same letter are not significantly different (P<0.05). Pairs of bars labelled *** (P<0.001) or NS indicates significance of the interaction between sowing code and species plant population.

Weed mass interaction	M.S	df	P value	US Weed Mass	M.S	df	Pvalue
Species	3.9877	10	<0.001	Species	0.005051	10	0.004
Sowing code	67.0393	1	<0.001	Residual	0.001837	119	
Species x Sowing code	3.8969	10	<0.001				

There were significant (P<0.001) differences in weed mass accumulation measured in August 2007 between straight sown FBCs, with perennial legumes, crimson clover (*T. incarnatum*) and peas (*P. sativum*) showing the highest weed t DM ha^{-1}. There were significantly (P<0.001) lower weed mass levels in the undersown FBCs and a highly significant (P<0.001) species x sowing code interaction demonstrated by fallow, crimson clover (*T. incarnatum*), black medic (*M. lupulina*) and peas (*P. sativum*)

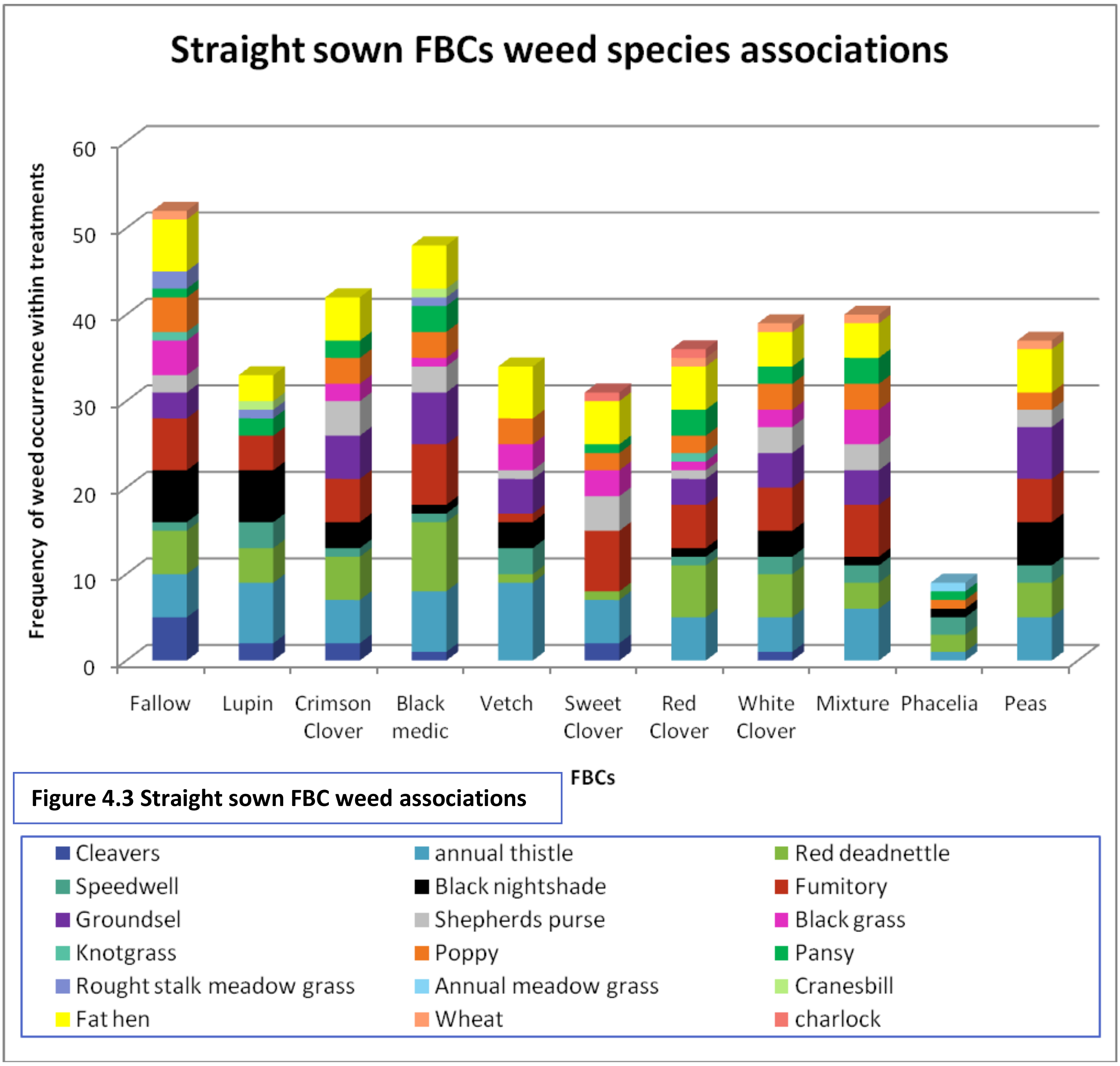


Figure 4.3 Straight sown FBC weed associations

A broad spectrum of weeds was present within the straight sown FBCs, consistent with a long term arable cropping situation, such as annual thistle (*Sonchus oleraceus* L), red deadnettle (*Lamium purpureum*), fumitory (*Fumaria officinalis*), black nightshade (*Solanum nigrum*) and fat hen (*Chenopodium album*). *Phacelia* had the lowest level of weeds due to its rapid establishment and N lifting capacity, followed by the erectile plants white lupins (*L. alba*) and sweet clover (*M. officinalis*). Black nightshade occurred in greatest quantities in the fallow, white lupin and peas (*P. sativum*).

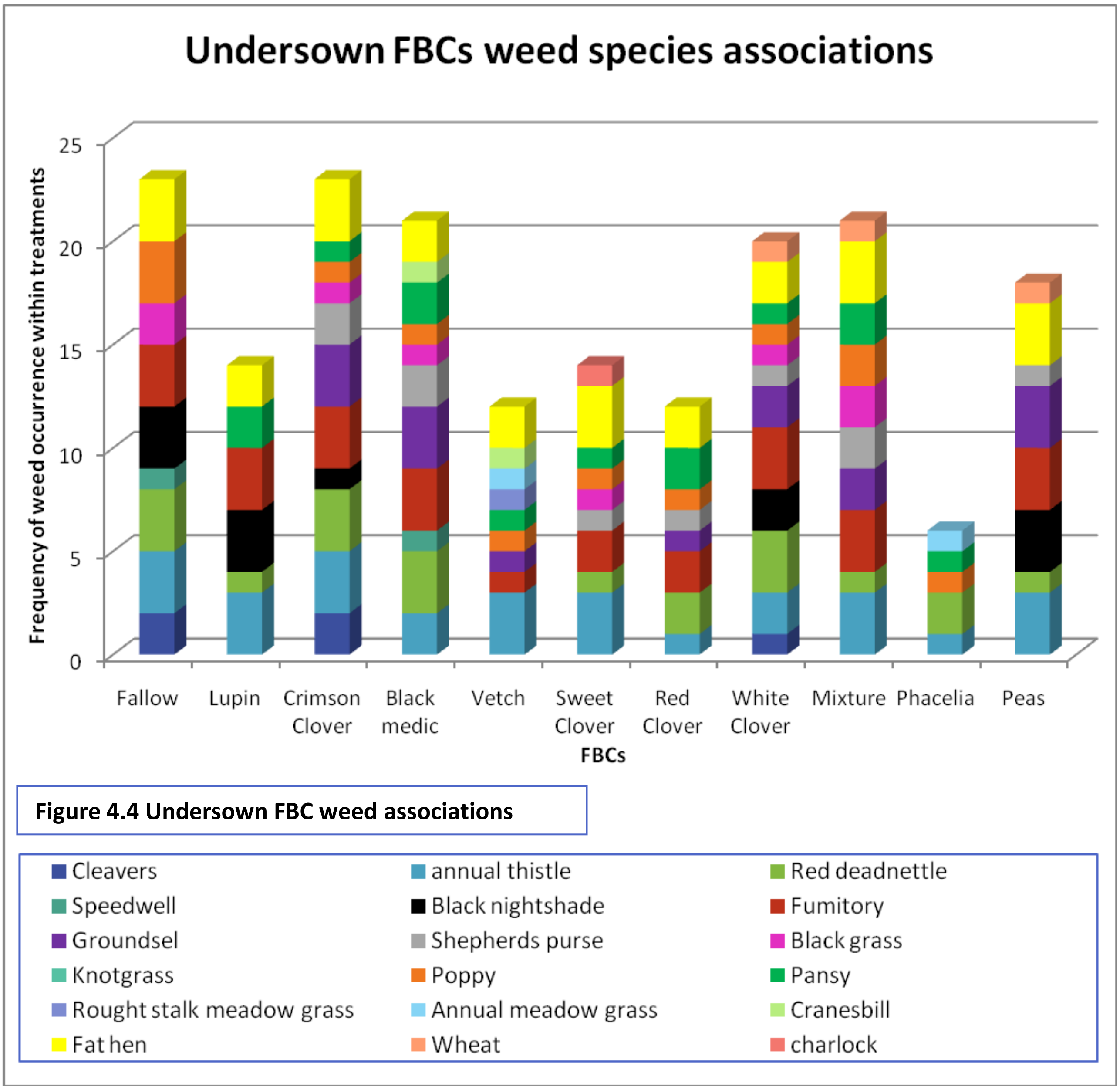


Figure 4.4 Undersown FBC weed associations

Undersown FBCs exhibited lower numbers of weed occurrences possibly due to the shading effect of the barley and FBCs, although differences in water and nutrient supplies may also have be implicated. The lowest and narrowest weed spectrum was demonstrated again by *Phacelia.* Uncompetitive perennials in establishment white clover (*T. repens*), black medic (*M. lupulina*) and poorly branched crimson clover (*T. incarnatum*) had a broad weed spectrum and high numbers of occurrences.

4.4.1.2 Straight sown FBCs

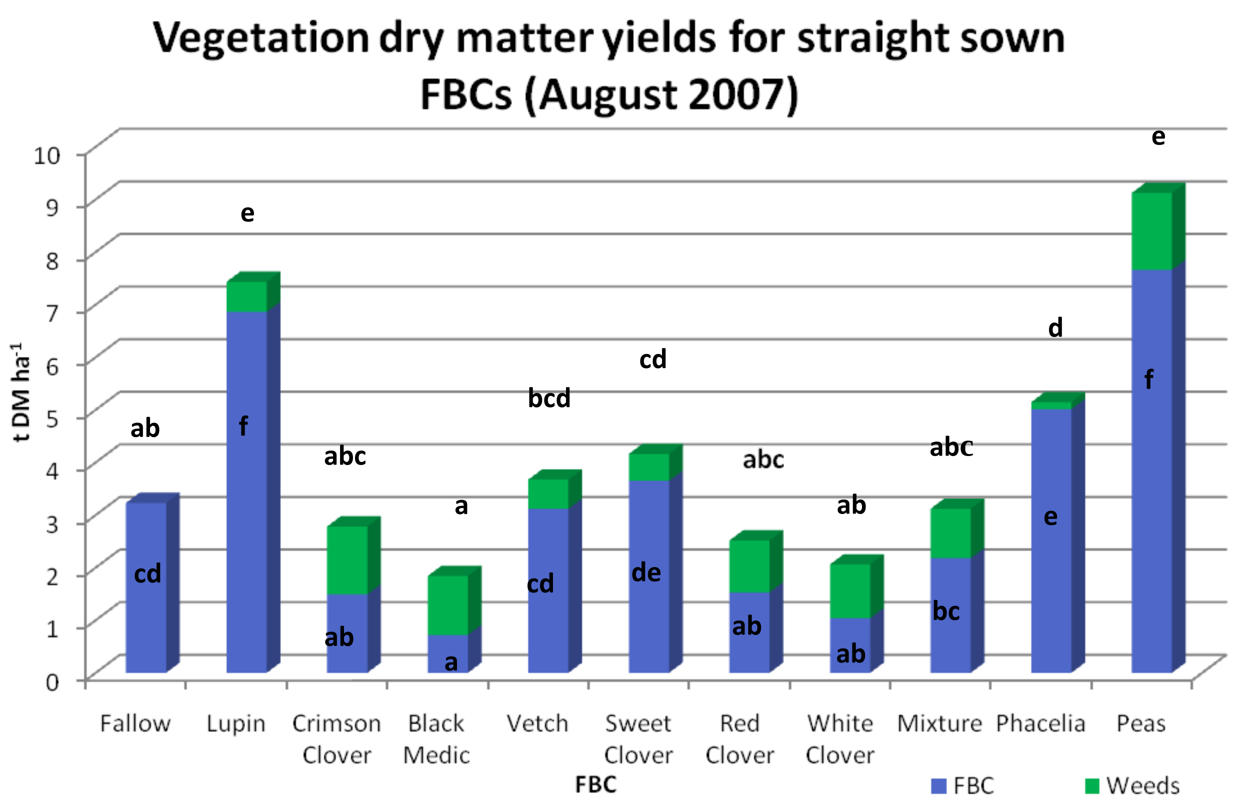


Figure 4.5 Vegetation DM yields for straight sown FBCs
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars and parts of bars with the same letter are not significantly different (P<0.05).

FBC	M.S	df	P value	FBC+ Weeds	M.S	df	P value
Species	65.039	10	<0.001	Species	76.641	10	<0.001
Residual	3.081	119		Residual	4.701	119	

Peas (*P. sativum)* and white lupins *(L. alba)* produced the highest levels of above-ground biomass, followed by *Phacelia,* vetch *(V. villosa)* and sweet clover (*M. officinalis).* Perennial species black medic (*M. lupulina)*, red clover (*T. pratense)*, white clover (*T. repens)* and the annual crimson clover (*T. incarnatum)* exhibited significantly (P<0.05) lower yields than the other FBCs, and significantly (P<0.05) higher weed levels. The mixture significantly (P<0.05) outperformed its constituent parts except for sweet clover (*M. officinalis).*

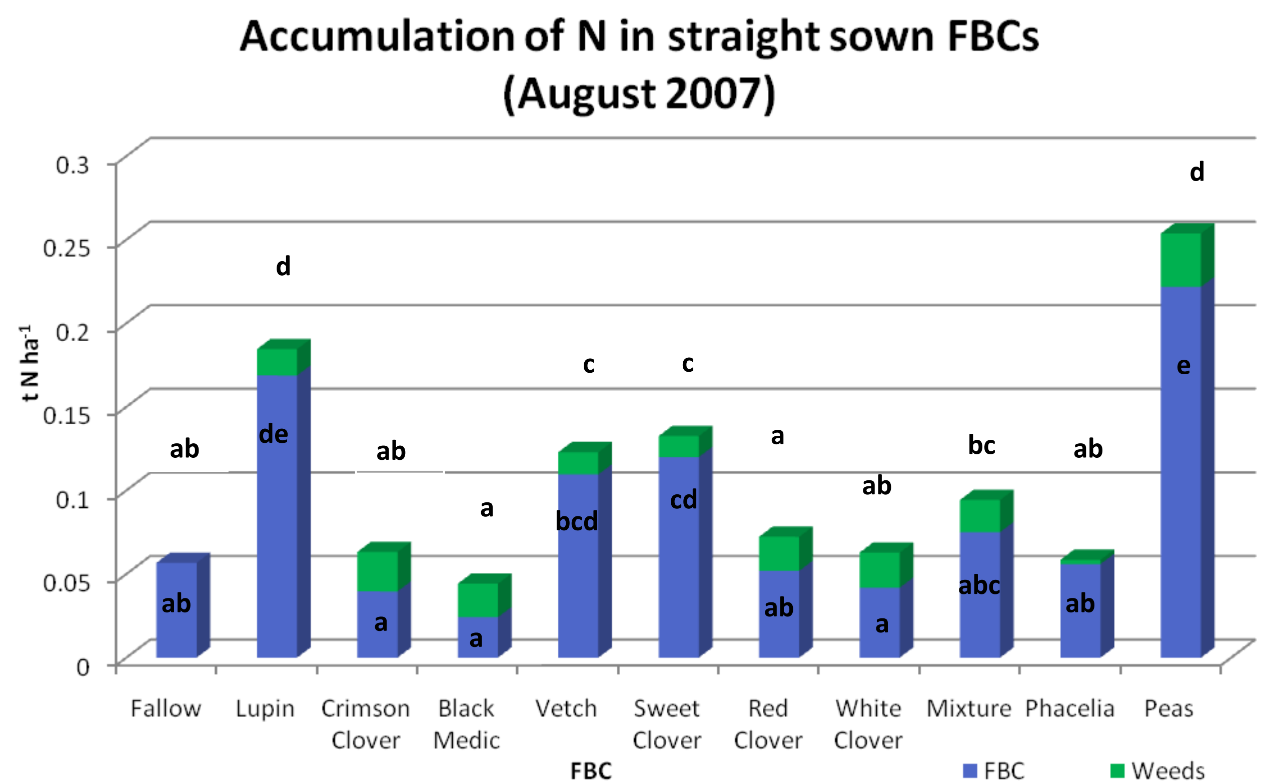


Figure 4.6 Accumulation of N in straight sown FBCs
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars and parts of bars with the same letter are not significantly different (P<0.05).

FBC	M.S	df	P value	FBC+ Weeds	M.S	df	P value
Species	0.045518	10	<0.001	Species	0.055283	10	<0.001
Residual	0.002	119		Residual	0.0024207	119	

Peas (*P. sativum)*, white lupin (*L. alba)*, vetch (*V. villosa*) and sweet clover (*M. officinalis*) accumulated significantly (P<0.05) greater levels of N in above-ground biomass than other FBCs, with white clover (*T. repens)*, black medic (*M lupulina)* and crimson clover (*T. incarnatum)* accumulating significantly lower levels. Total N accumulations (additive contributions from FBCs and weeds) were highest in the annual and biennial legume species with the exception of crimson clover (*T. incarnatum).* N accumulation in the non-legumes was comparable with perennial legume levels.

4.4.1.3 Undersown FBCs

The spring barley crop covering the undersown sowing regime treatments was combined on the 17th August 2007 after an above-ground vegetation samples harvest. Excess material above stubble height was swathed, baled and removed.

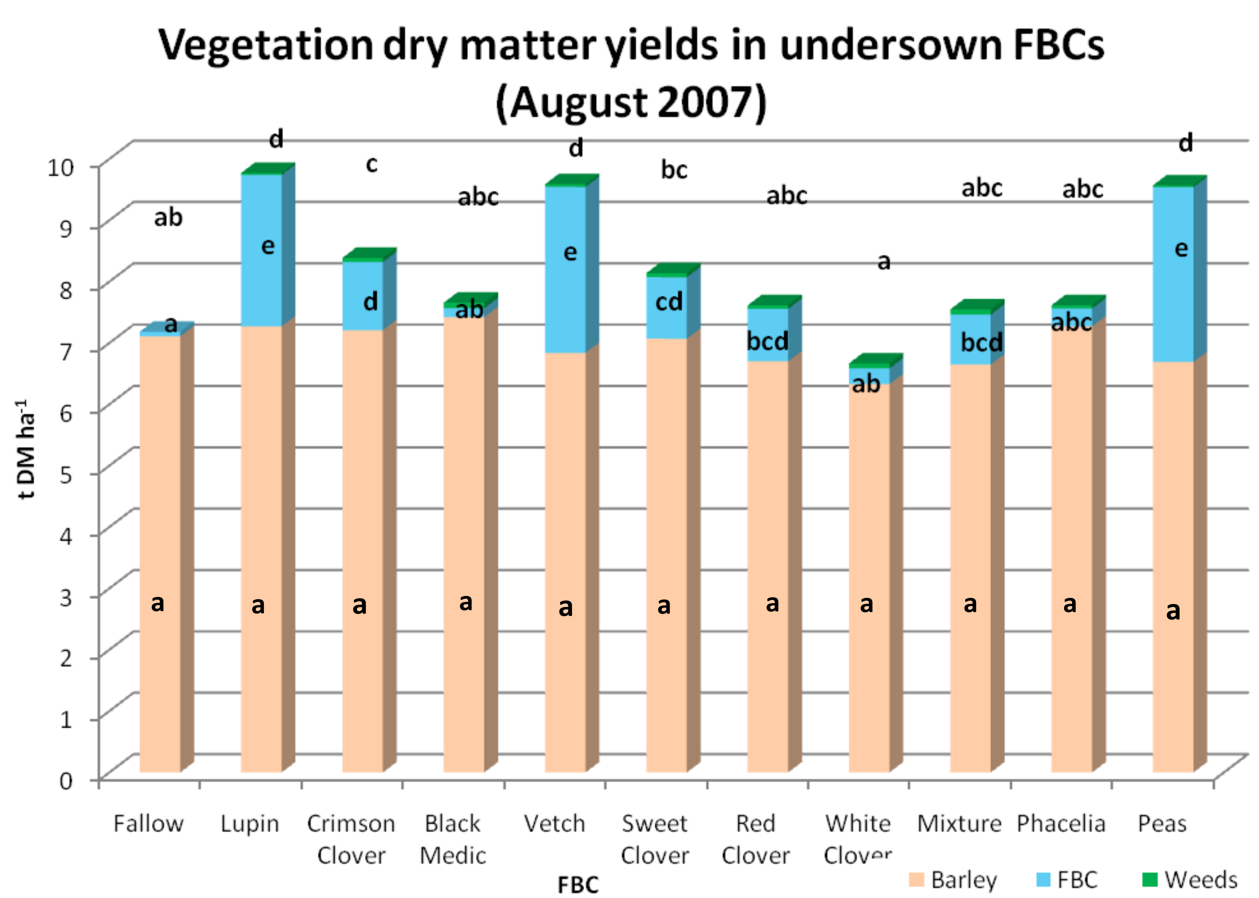


Figure 4.7 Vegetation DM yields in undersown FBCs.
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars and parts of bars with the same letter are not significantly different (P<0.05).

FBC	M.S	df	P value	Total	M.S	df	P value
Species	13.1685	10	<0.001	Species	13.294	10	<0.001
Residual	0.8224	119		Residual	2.052	119	

Barley whole crop DM yields were taken from the 19th July to the 3rd August 2007 and averaged 6.96 t DM ha^{-1}. There were no significant differences, positive or negative, between FBC treatments. FBC yields varied significantly, with the greatest DM yields expressed by annual and biennial species, red clover (*T. pratense*) and the mixture. Significantly (P<0.05) lower DM yields were recorded for the perennial and non-legume species. Total DM yield offtake was a reflection of the FBC performance with significantly (P<0.05) lower levels from white clover (*T. repens)* and fallow. Highest DM yields were demonstrated by white lupin (*L. alba)*, vetch (*V. villosa)* and peas (*P. sativum).*

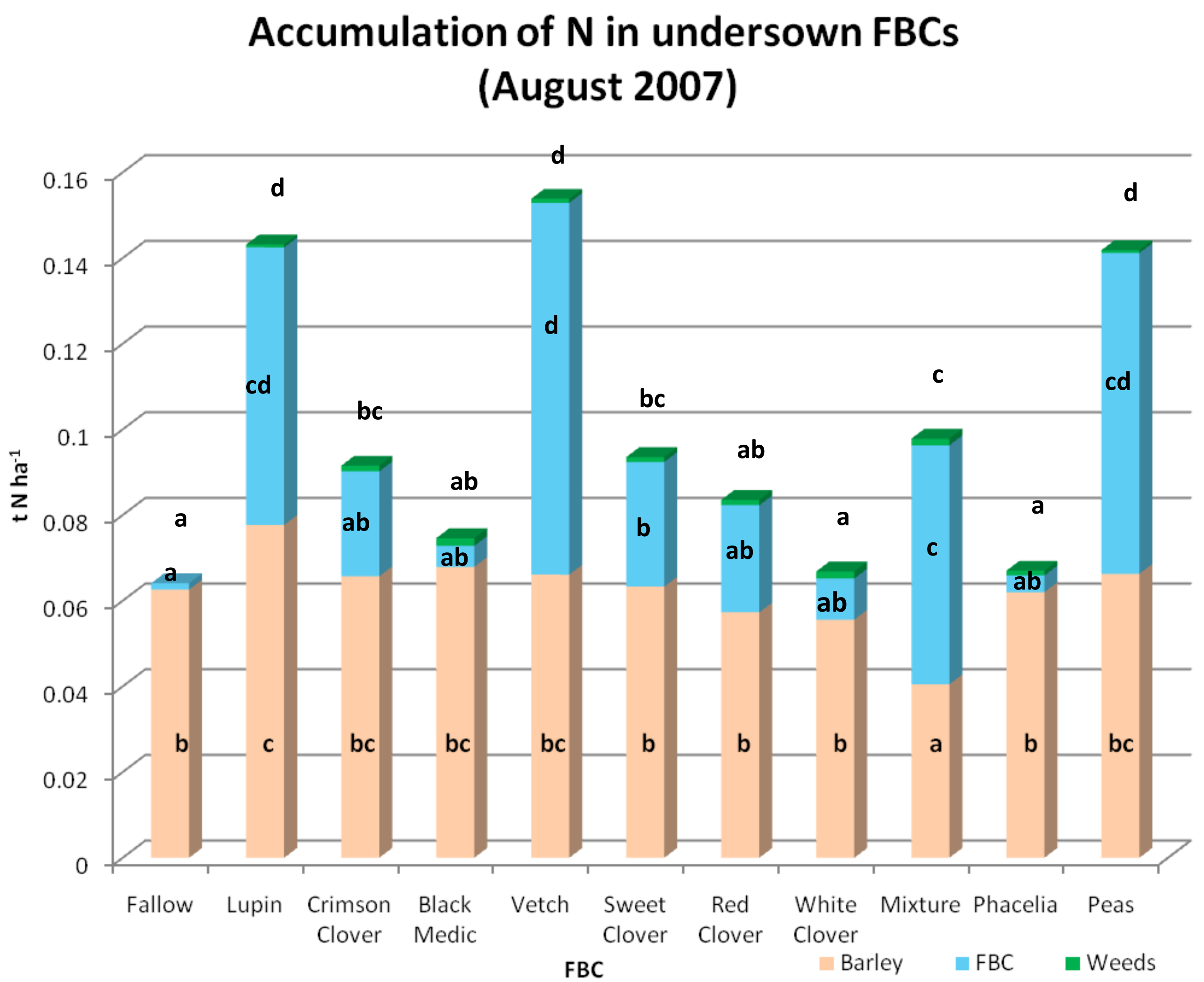


Figure 4.8 Accumulation of N in undersown FBCs
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars and parts of bars with the same letter are not significantly different (P<0.05).

FBC	M.S	df	P value
Species	0.011382	10	<0.001
Residual	0.001003	119	

Total	M.S	df	P value
Species	0.00132892	10	<0.001
Residual	0.0008062	119	

Barley t N ha^{-1}	M.S	df	P value
Species	0.0010293	10	<0.001
Residual	0.0003017	119	

Barley N accumulation levels were all comparable with the exception of plots undersown with the mixture and with white lupins (*L. alba)* which were significantly ($P<0.05$) lower and higher respectively (See appendix 3.2.1.2). N accumulations by the annual FBCs and the mixture were significantly greater ($P<0.05$) than the other FBCs. Non-legumes, perennial species and crimson clover (*T. incarnatum)* exhibited comparable and lower N accumulation figures.

The total N accumulation for each FBC treatment shown comprised of barley, FBC, and weed N contributions. Lowest total N accumulation was demonstrated by non-legumes and perennial legumes and the highest levels by vetch, (*V. villosa)*, white lupin (*L. alba)* and peas (P*. sativum).*

4.4.1.4 Overwintered FBCs

FBCs were mulched on the 17th August 2007, residues remained on the surface and FBCs were allowed to regenerate. FBCs which overwintered in appreciable levels were sampled on the 13th February 2008. Overwintered FBCs were black medic (*M. lupulina*), white clover (*T. repens*), the mixture and *Phacelia,* all from the straight sown sowing regime. *Phacelia* had mainly regenerated from shed seeds rather than from the original plants.

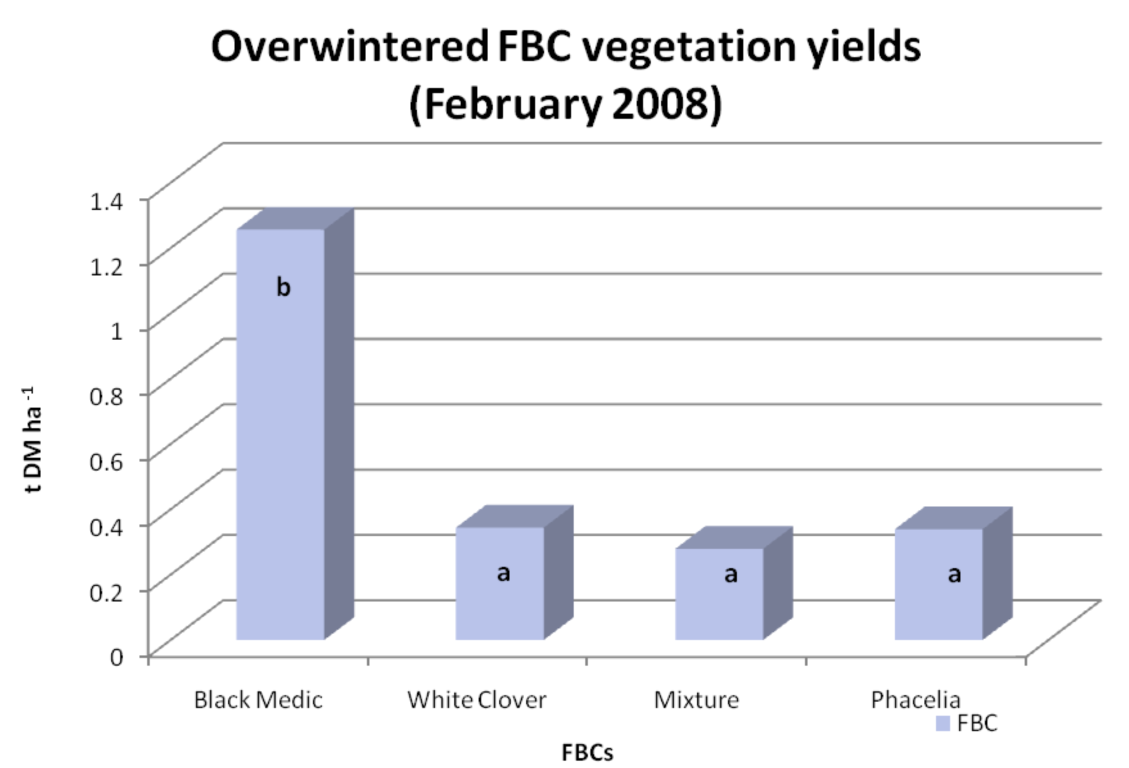


Figure 4.9 Overwintered FBC vegetation DM yields.

Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars with the same letter are not significantly different (P<0.05).

FBC	M.S	df	P value
Species	1.31855	3	<0.001
Residual	0.05849	18	

Black medic (*M. lupulina*) produced significantly (P<0.001) greater levels of above-ground biomass (t DM ha^{-1}) compared to the other overwintered FBCs. No measurable quantity of weed material was present within the FBC samples.

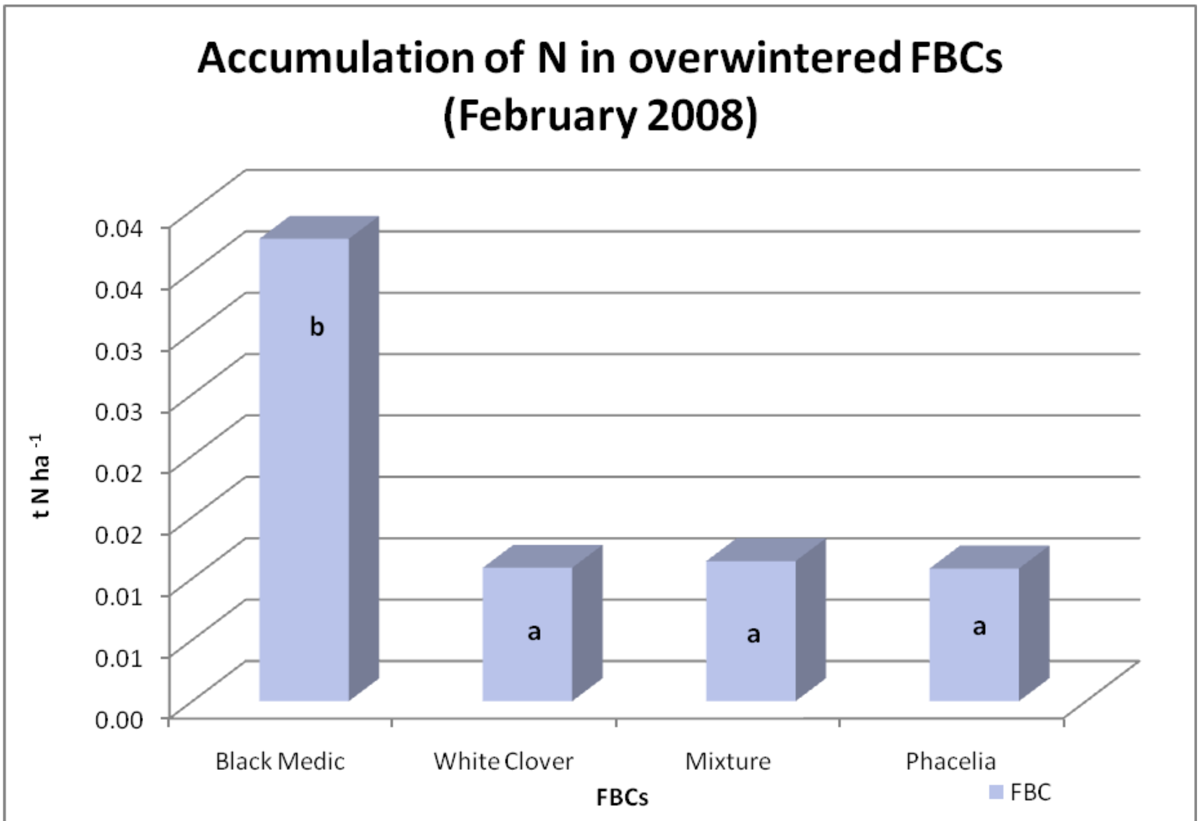


Figure 4.10 Accumulation of N in overwintered FBCs
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars with the same letter are not significantly different (P<0.05).

FBC	M.S	df	P value
Species	0.00106488	3	<0.001
Residual	0.00008258	18	

Accumulation of N in overwintered FBCs was a reflection of the DM yield, with black medic (*M. lupulina*) significantly (P<0.001) out yielding all other FBCs.

Table 4.4 – Vegetation quality analysis

FBC	Straight Sown FBCs C:N ratios			Undersown FBCs C:N ratios			Overwintered FBCs C:N ratios		
	FBC (above-ground)	*FBC + weeds*	*Total **	*FBC (above-ground)*	*FBC + barley + weeds*	*Below-ground ***	*FBC (above-ground)*	*Below-ground ****	*Total *****
Fallow	22.78 e	22.27 e	21.04 e	18.54 f	48.64 d	30.87 e			
Lupin	17.88 d	17.85 d	17.69 d	16.84 e	29.91 a	31.72 d			
Crimson Clover	16.13 c	18.91 d	17.96 d	18.93 f	39.39 bc	25.99 b			
Black Medic	13.17 c	18.33 d	17.70 d	12.28 a	44.22 cd	25.37 a	14.72 c	9.84 c	16.96
Vetch	12.52 b	13.08 a	13.17 a	13.25 bc	28.02 a	26.92 b			
Sweet Clover	13.3 b	13.66 ab	13.93 ab	14.74 d	37.34 b	23.5 a			
Red Clover	12.63 b	15.11 bc	14.48 bc	14.09 cd	39.44 bc	23.47 a			
White Clover	10.6 a	14.28 ab	13.82 ab	12.51 ab	43.12 bcd	28.78 c	13.32 bc	9.05 b	16.85
Mixture	12.37 b	14.22 abc	13.95 ab	13.19 bc	33.64 a	23.04 a	9.76 a	9.85 c	15.01
Phacelia	36.62 f	35.95 f	35.04 f	29.97 g	48.83 d	36.42 e	12.36 b	4.82 a	15.56
Peas	15.21 c	15.65 c	15.68 c	16.5 e	31.55 a	28.25 c			
LSD (P<0.05)	**1.68**	**2.01**	**1.705**	**1.22**	**4.46**	**1.141**	**2.46**	**0.1670**	**2.430**

C:N ratio values within the same column followed by the same letter superscript are not significantly different (P<0.05). Unless otherwise stated C:N ratios relate to above-ground material.

* Total = above-ground FBC + Weeds + estimated below-ground residue from pot trial.
** Below-ground = estimated below-ground residue from pot trial.
*** Below-ground = estimated below-ground residue from overwintered pot trial.
**** Total = above-ground overwintered FBC + overwintered weeds + estimated below-ground residue from overwintered pot trial
.

The non-legumes fallow and *Phacelia* across both sowing regimes (with the exception of the overwintered *Phacelia*) gave the highest C:N ratios, well above the mineralisation immobilisation balance point (assumed as 20:1 from 4.1.2 St. Luce *et al.,* (2011), Tejada *et al.,* (2008) and Frankenberger and Abdekmagid (1985)). All legume FBCs had C:N ratios below the balance point. "Total" was FBC + weeds and/or barley stubble if undersown. Thus the total residue C:N ratio for all undersown FBCs were in excess of the balance point suggesting a potential modification in residue behaviour once incorporated over the straight sown FBC residues.

Below-ground contributions were based on estimates from the pot experiment, to compile whole plant and below-ground C:N ratios. The basis for transferring this data from the pot experiment was an apparently significant ($P<0.001$ $R^2=0.673$) relationship (Appendix 3.2.1.5) between the above-ground pot experiment shoots and field trial above-ground C:N ratios. Below-ground analysis (root material) is appropriate in the undersown sowing regimes as all material above the stubble height was removed.

"Whole plant" was above-ground FBC + weeds, with estimates of below-ground residues. All residues in the straight sown sowing regime exhibited ratios below the mineralisation immobilisation point with the exception of the fallow and *Phacelia*.

Increases in the C:N ratio of white clover (*T. repens*) and black medic (*M. lupulina*) after overwintering probably represented an increase in maturity. Sweet clover (*M. officinalis*) did not overwinter successfully, hence the reduction in C:N ratio shown by the mixture in the overwintered FBCs column. "Overwintered" *Phacelia* was mostly regenerated from shed seed and plants were mostly immature on the sampling date in February 2008. Whole plant analysis showed no significant differences ($P<0.05$) between the overwintered species.

4.4.1.5 Soil status at the commencement of test crop monitoring

SON and SOC levels averaged 0.438% and 6.93% across the trial site. There were no significant differences between FBCs or sowing code treatments (Appendix 3.2.2.1).

4.4.2 Performance of Winter Wheat test Crop

4.4.2.1 Soil monitoring

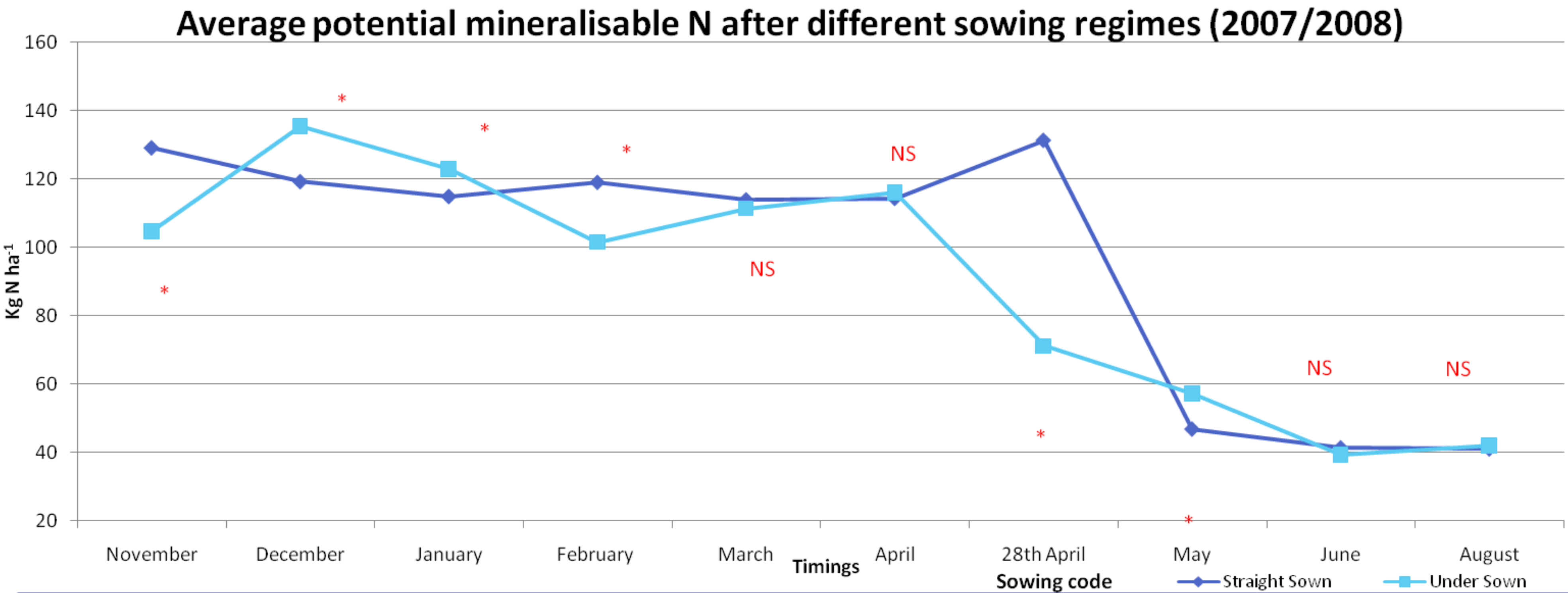


Figure 4.11 Winter wheat average potential mineralisable N after differing sowing regimes
Meaned data sets, Repeated measures ANOVA analysis with Fishers protected multiple range test.Individual timings ANOVA analysis, * or NS indicates signficance (P<0.05) of timing analysis.

FBC species	M.S	df	P value	Timings	M.S	df	P value
Species	12723.1	10	<0.001	Timings	157624.2	9	<0.001
Sowing code	15975.0	1	0.013	Time x Species	763.0	90	0.007
Species x Sowing code	5155.1	10	0.034	Time x Sowing code	16446.1	9	<0.001
Residual	2504.2	108		Time x Species x Sowin g code	771.1	90	0.006
				Residual	496.7	990	

Sowing regimes significantly influenced PMN (P<0.013), and there was a highly significant (P<0.001) interaction between sowing code and sampling timing. Individual timings showed significant (P<0.05) differences between the sowing regimes in November, December, January, February, 28th April and May.

Table 4.5 – FBC mean soil PMN values (kg N ha^{-1}) across sowing regimes

Timings	***FBC***											***Timings Mean***
	Fallow	***Lupin***	***Crimson Clover***	***Black Medic***	***Vetch***	***Sweet Clover***	***Red Clover***	***White Clover***	***Mixture***	***Phacelia***	***Peas***	
November	120.73	113.49	118.22	122.31	118.59	96.27	122.14	120.22	123.55	129.56	101.28	**116.94**
December	115.91	129.89	132.95	133.51	131.57	113	142.24	122.72	130.14	138.08	110.71	**127.33**
January	111.43	138.97	111.45	119.87	123.85	100.1	126.79	126.88	130.58	119.37	98.49	**118.89**
February	92.18	125.81	99.41	114.51	130.98	86.18	122.32	109.85	109.61	128.58	93.84	**110.3**
March	110.06	115.18	116.88	121.92	112.49	86.57	128.02	112.18	116.81	125.1	93.98	**112.66**
April	100.91	124.39	102.27	133.19	126.22	88.27	135.94	112.27	114.24	133.33	96.43	**115.22**
28th April	83.19	109.18	92.01	98.95	142.73	78.71	126.26	91.34	90.21	127.76	73.25	**101.24**
May	48.76	59.51	49.31	54.26	56.89	42.98	58.45	50.22	52.67	53.91	45.89	**52.08**
June	32.86	46.05	34.73	44.78	44.38	30.85	44.73	38.75	41.73	47.5	38.08	**40.4**
August	37.49	42.93	46.79	49.73	46.7	30.64	41.29	37.78	41.98	45.14	37.26	**41.61**
Species Mean	**85.35 ^{abc}**	**100.54 ^{de}**	**90.4 ^{bcd}**	**99.3 ^{de}**	**103.44 ^{e}**	**75.36 ^{a}**	**104.82 ^{e}**	**92.22 ^{cde}**	**95.15 ^{cde}**	**104.83 ^{e}**	**78.92 ^{ab}**	

Species mean values followed by the same letter superscript are not significantly different (P<0.05)

The 10 month mean soil PMN values varied significantly (P<0.05) between the species across the sowing regimes. Crops with significantly (P<0.05) lower average PMN levels were sweet clover *(M. officinalis)*, peas (*P. sativum*) and fallow. Crops which produced the highest levels were white clover (*T. repens*), the mixture, black medic (*M. lupulina*), lupin (*L. alba*), vetch (*V. villosa*), red clover (*T. pratense*) and *Phacelia*.

Table 4.6 –Mean soil PMN values (kg N ha^{-1}) within the different sowing regimes

Timings	*Straight Sown*	*Undersown*
November	129.14 ^{d}	104.74 ^{ef}
December	119.25 ^{d}	135.42 ^{i}
January	114.91 ^{d}	122.87 ^{ghi}
February	119.04 ^{d}	101.56 ^{e}
March	113.92 ^{d}	111.39 ^{efg}
April	114.37 ^{d}	116.07 ^{efgh}
28th April	131.33 ^{d}	71.14 ^{cd}
May	46.92 ^{abc}	57.23 ^{abc}
June	41.44 ^{ab}	39.36 ^{a}
August	41.13 ^{a}	42.09 ^{ab}
Sowing code Mean	**97.15 ^{b}**	**90.19 ^{a}**

Values followed by the same letter superscript are not significantly different (P<0.05)

Figure 4.11 indicates significant (P<0.013) differences in soil PMN levels between the sowing regimes and a significant (P<0.001) interaction between sampling timings and sowing regimes. Table 4.16 allows further examination of the disparity between sowing regimes and PMN levels. Straight sown FBCs had a significantly (P<0.05) (but only slightly higher) average value than undersown (97.15kg N ha^{-1} versus 90.19 kg N ha^{-1}). Straight sown FBCs demonstrated consistent levels of PMN from November 2007 to the end of April 2008. The initial undersown release pattern, does not mirror that of the straight sown treatments and peak levels occurred in December and January. There was also a significant (P<0.05) decline in April relative to the straight sown treatments.

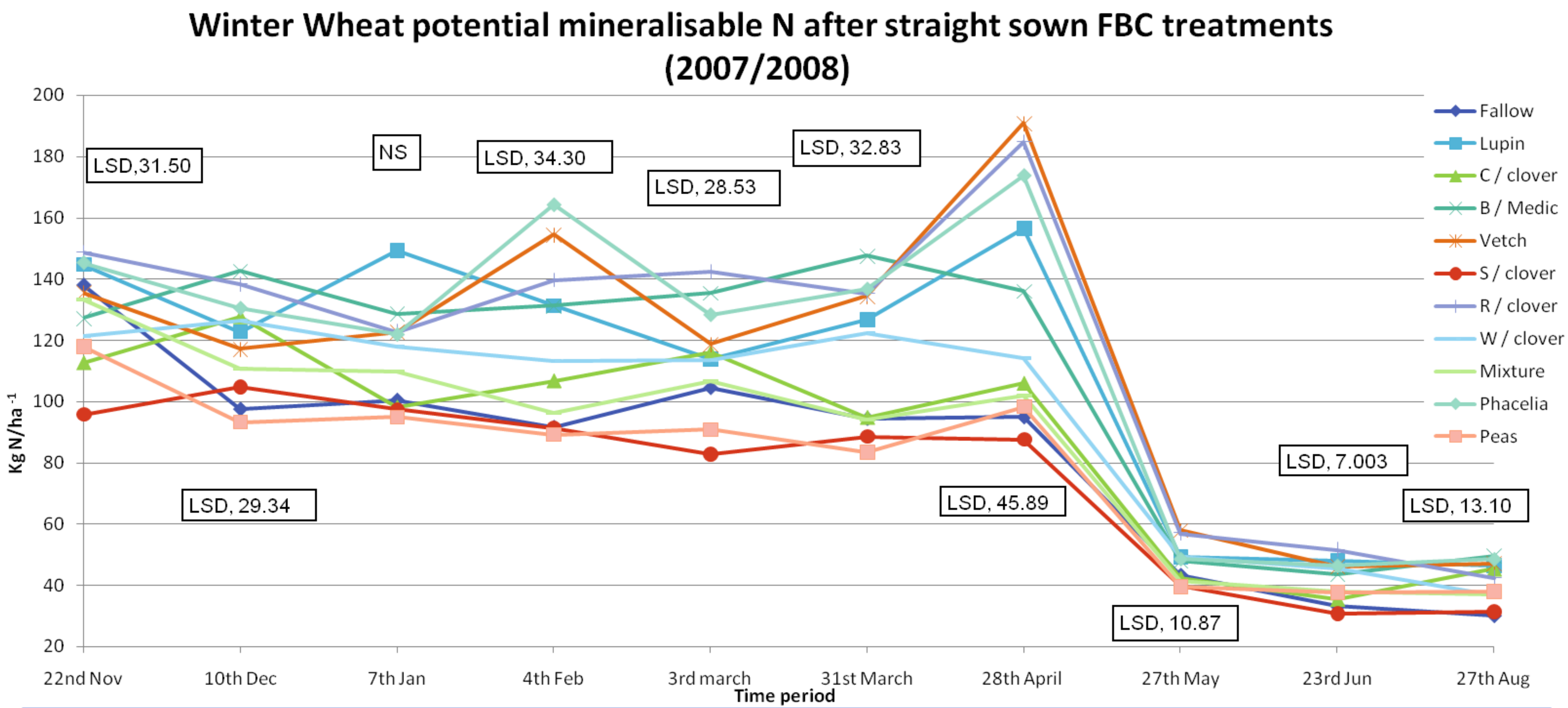


Figure 4.12 Winter wheat potential mineralisable N after straight sown FBC treatments.
Meaned data sets, Repeated measures ANOVA analysis with Fishers protected multiple range test. Individual timings ANOVA analyses, all significant (P<0.05) except for January, LSD for each timing displayed

FBC species	M.S	df	P value
Species	14477.5	10	<.001
Residual	2974.8	53	

Timings	M.S	df	P value
Timings	93986.5	9	<.001
Time. Species	1064.5	90	<.001
Residual	514.6	495	

Figure 4.12 shows highly significant (P<0.001) differences between FBCs PMN over the sampling period and (P<0.05) differences at individual timings. There was also a highly significant species x timings interaction.

Table 4.7 – Winter wheat soil PMN levels (kg N ha^{-1}) after straight sown FBC treatments

FBCs	*Timings (2008)*				
	4th Feb	*3rd March*	*31st March*	*28th April*	*27th May*
Fallow	91.7 ^{a}	104.6 ^{abc}	94.5 ^{ab}	95 ^{ab}	43.3 ^{a}
Lupin	131.1 ^{bc}	113.9 ^{bcde}	126.6 ^{bc}	156.5 ^{cde}	49.3 ^{ab}
Crimson Clover	106.7 ^{ab}	115.9 ^{bcde}	94.7 ^{ab}	105.8 ^{ab}	42.3 ^{a}
Black Medic	131.2 ^{bc}	135.4 ^{de}	147.6 ^{c}	136 ^{bcd}	47.9 ^{ab}
Vetch	154.5 ^{c}	118.7 ^{bcde}	134.4 ^{c}	190.9 ^{e}	57.9 ^{b}
Sweet Clover	91.3 ^{a}	82.9 ^{a}	88.6 ^{a}	87.7 ^{a}	39.8 ^{a}
Red Clover	139.7 ^{bc}	142.3 ^{e}	135.2 ^{c}	184.7 ^{e}	57.1 ^{b}
White Clover	113.2 ^{ab}	113.6 ^{bcd}	122.3 ^{bc}	114 ^{abc}	49.2 ^{ab}
Mixture	96.4 ^{a}	106.7 ^{abc}	94 ^{ab}	101.9 ^{ab}	41.3 ^{a}
Phacelia	164.3 ^{c}	128.4 ^{cde}	136.8 ^{c}	173.9 ^{de}	48.6 ^{ab}
Peas	89.1 ^{a}	90.7 ^{ab}	83.4 ^{a}	98.2 ^{ab}	39.5 ^{a}
LSD (P<0.05)	**34.3**	**28.53**	**32.83**	**45.89**	**10.87**

Values followed by the same letter superscript are not significantly different (P<0.05)

Table 4.7 covers key winter wheat development periods when fluctuations in soil PMN levels could have an impact on crop development and yield. The table clarifies the levels of soil PMN after individual FBC treatments samples throughout the spring of 2008. Peak levels for sweet clover (*M. officinalis*) occurred on 4th February and on 3rd of March for the fallow, crimson clover (*T. incarnatum*) and the mixture. The prostrate perennial legumes (*M. lupulina* and *T. repens)* peaked on 31st March and the remaining FBCs peaked on 28th April. Appropriate LSDs are shown in the table and on figure 4.12.

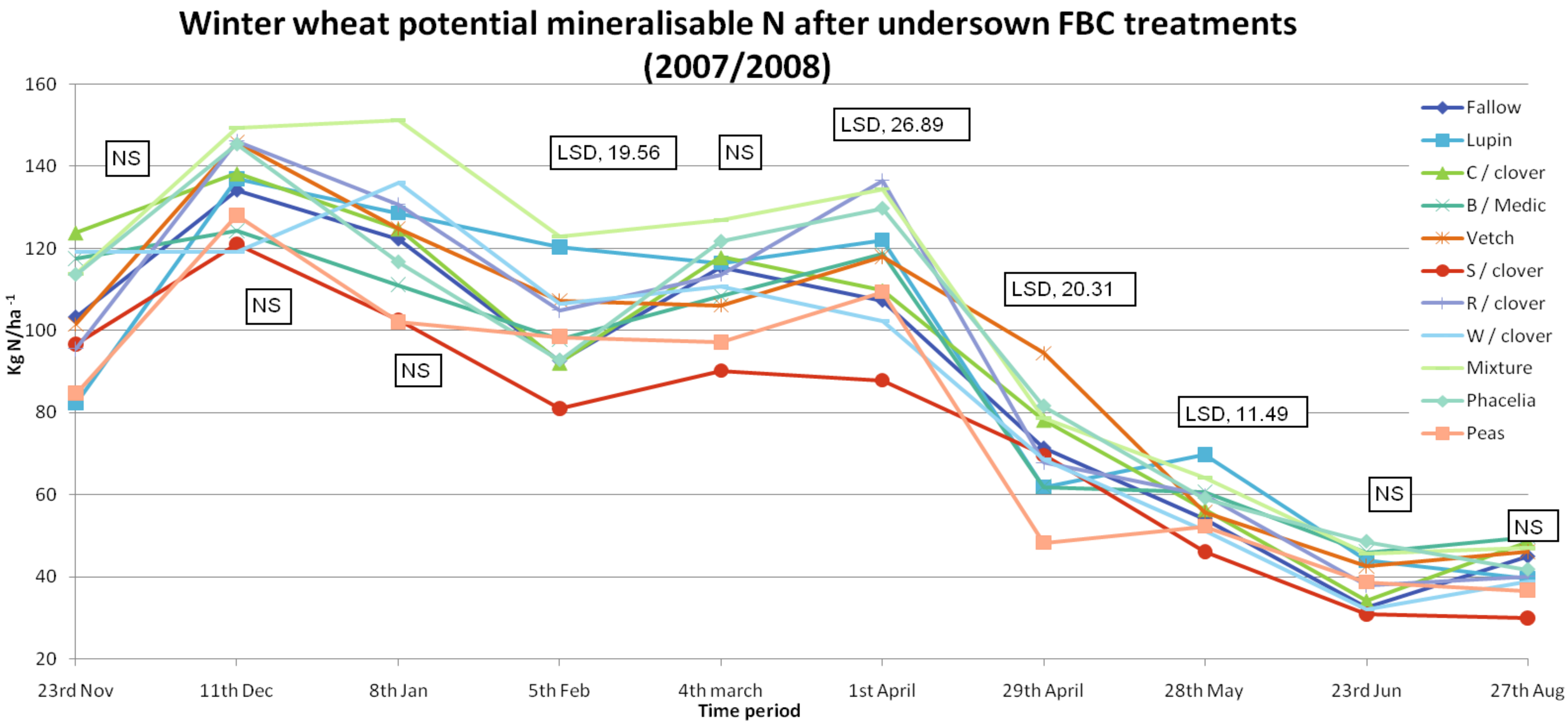


Figure 4.13 Winter wheat potential mineralisable N after undersown FBC treatments.
Meaned data sets, Repeated measures ANOVA analysis with Fishers protected multiple range test. Individual timings ANOVA analysis, LSD or NS indicates signficance (P<0.05) of timing analysis.

FBC species	M.S	df	P value
Species	3400.7	10	0.080
Residual	1872.5	53	

Timings	M.S	df	P value
Timings	80083.8	9	<.001
Time. Species	469.7	90	0.516
Residual	478.9	495	

There were no significant differences in PMN values over the whole growing season between FBC treatments. However, there were significant differences (P<0.05) at specific sample timings in February, April and May.

Table 4.8 – Winter wheat soil PMN levels (kg N ha^{-1}) after undersown FBC treatments

FBCs	*Timings (2008)*			
	5th Feb	*1st April*	*29th April*	*28th May*
Fallow	92.6 ^{ab}	107.3 ^{abc}	71.4 ^{b}	54.2 ^{abc}
Lupin	120.3 ^{c}	122.1 ^{bcde}	61.8 ^{ab}	69.7 ^{d}
Crimson Clover	92.1 ^{ab}	109.8 ^{abcd}	78.2 ^{bc}	56.4 ^{abc}
Black Medic	97.9 ^{ab}	118.8 ^{bcde}	61.9 ^{ab}	60.7 ^{bcd}
Vetch	107.4 ^{bc}	118.1 ^{bcde}	94.6 ^{c}	55.8 ^{abc}
Sweet Clover	81.1 ^{a}	87.9 ^{a}	69.7 ^{b}	46.1 ^{a}
Red Clover	105 ^{bc}	136.7 ^{e}	67.8 ^{ab}	59.8 ^{bcd}
White Clover	106.5 ^{bc}	102.2 ^{ab}	68.7 ^{b}	51.2 ^{ab}
Mixture	122.8 ^{c}	134.5 ^{de}	78.5 ^{bc}	64.1 ^{cd}
Phacelia	92.8 ^{ab}	129.8 ^{cde}	81.6 ^{bc}	59.2 ^{bcd}
Peas	98.6 ^{ab}	109.5 ^{abcd}	48.3 ^{a}	52.3 ^{ab}
LSD (P<0.05)	**19.56**	**26.89**	**20.31**	**11.49**

Values followed by the same letter superscript are not significantly different (P<0.05)

Table 4.8 covers the important periods for development of winter wheat. Peak soil PMN values for all species occurred on 1st April with the exception of white clover (*T. repens)* which peaked on 5th February.

4.4.2.2. Vegetation monitoring

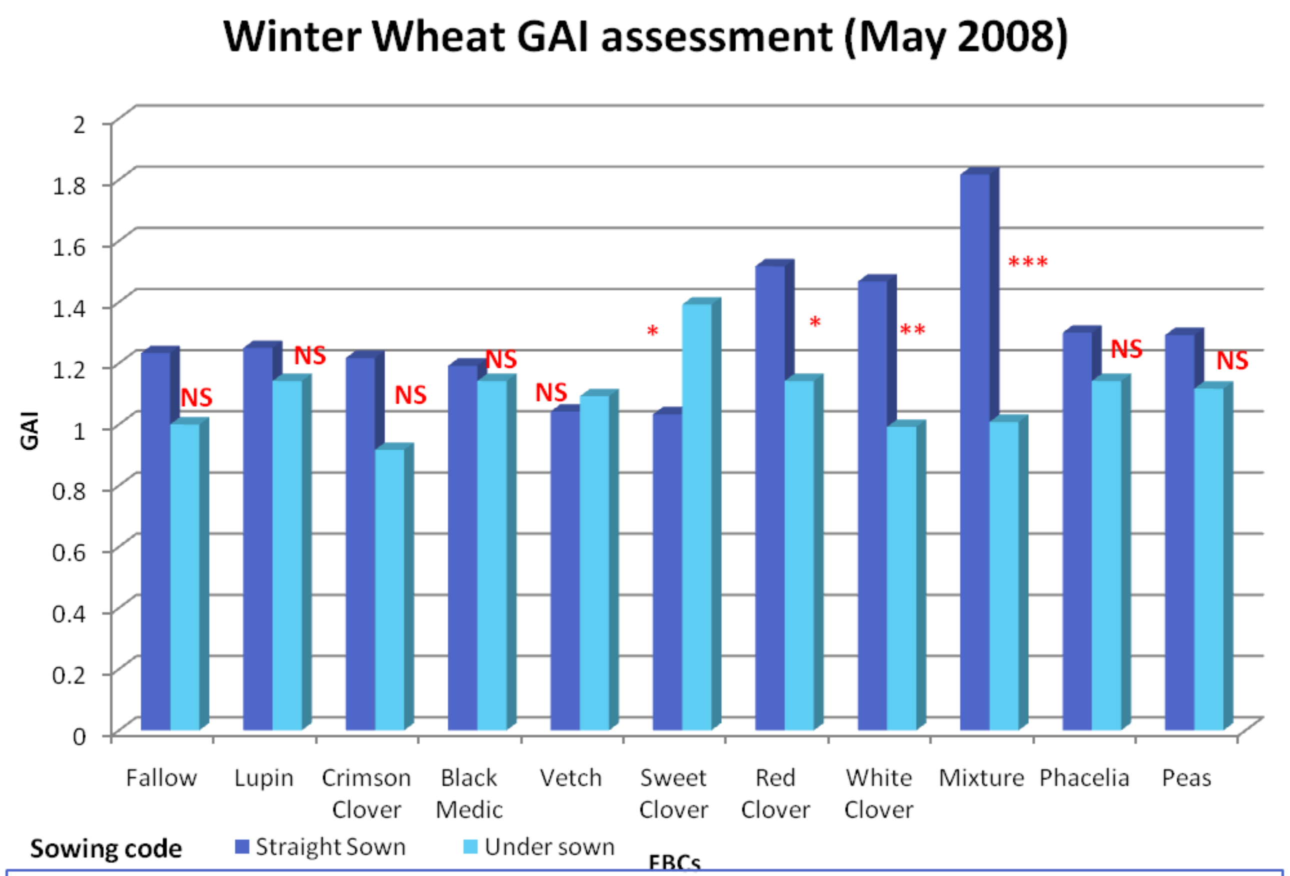


Figure 4.14 Winter wheat GAI assessment

Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Pairs of bars labelled * (P<0.05) ** (P<0.01) *** (P<0.001) or **NS** indicates the significance of the interaction between sowing code and species LAIs.

FBCs	M.S	df	P
Species	0.2565	10	0.095
Sowing code	2.8231	1	<0.001
Species x Sowing code	0.5367	10	0.001
Residual	0.1560	240	

Winter wheat test crop GAI (green area index) was assessed on the 12th May 2008 whilst the crop was at GS 32 (stem extension). GAI showed no significant differences between wheat plots grown after different FBCs, but significantly (P<0.001) lower levels following the undersown FBCs. There was also a significant (P<0.001) species x sowing code interaction. Sweet clover (*M. officinalis*) and red clover (*T. pratense*) had significantly (P<0.05) higher and lower GAIs in the undersown than the straight sown FBC plots respectively. Wheat grown after white clover (*T. repens*) and the mixture showed more significant (P<0.01 and P<0.001) levels of GAI after straight sowing compared to undersowing.

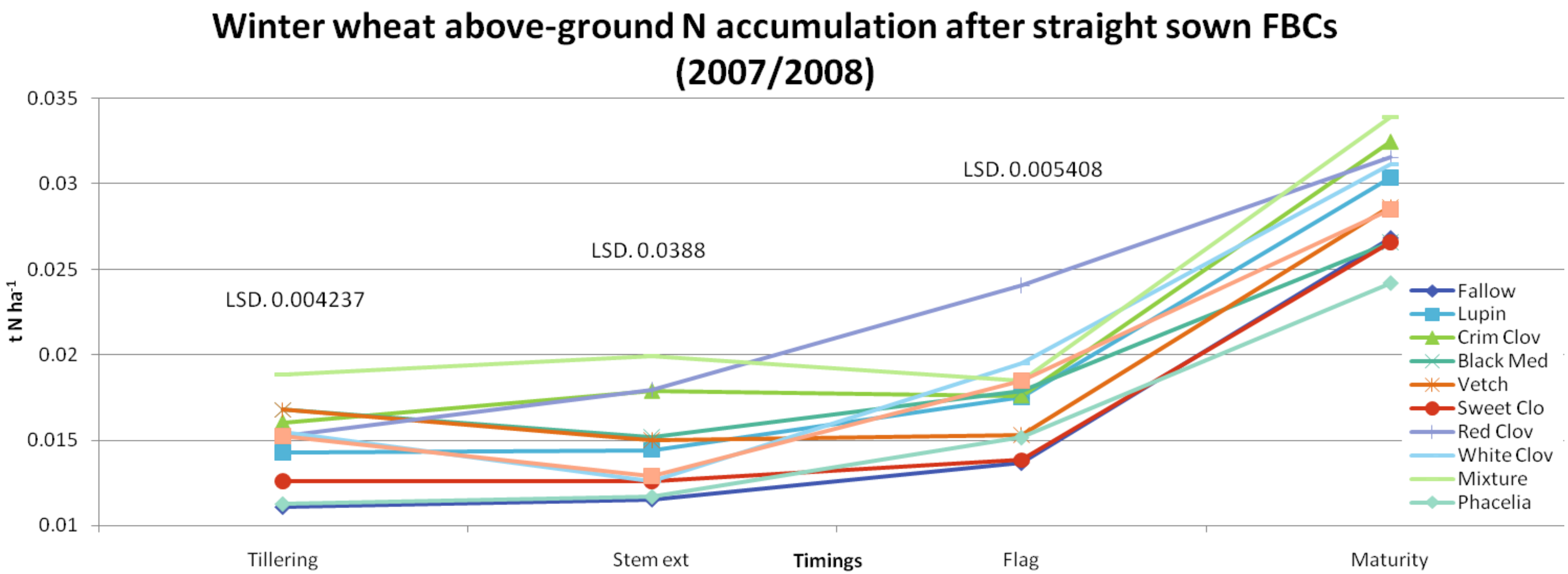


Figure 4.15 Winter wheat and weeds N accumulation after straight sown FBCs

Meaned data sets, Repeated measures ANOVA analysis with Fishers protected multiple range test. Timings analysed by split plot ANOVA, significant ($P<0.05$) differences are denoted by their LSDs posted on graphs.

FBC species	M.S	df	P value	Timings	M.S	df	P value
Species	0.0001392	10	< .001	Timings	0.0031114	3	<.001
Residual	0.00002678	53		Time x Species	0.00001622	30	0.974
				Residual	0.00003198	165	

Winter Wheat test crop accumulation of N, demonstrates highly significant differences between FBC over the growing season and significant ($P<0.05$) differences at tillering, stem extension and flag leaf emergence, with no significant differences between FBCs at maturity. N accumulated shows a highly significant ($P<0.001$) relationship to sampling timing, a reflection of the nature of crop development over a growing season.

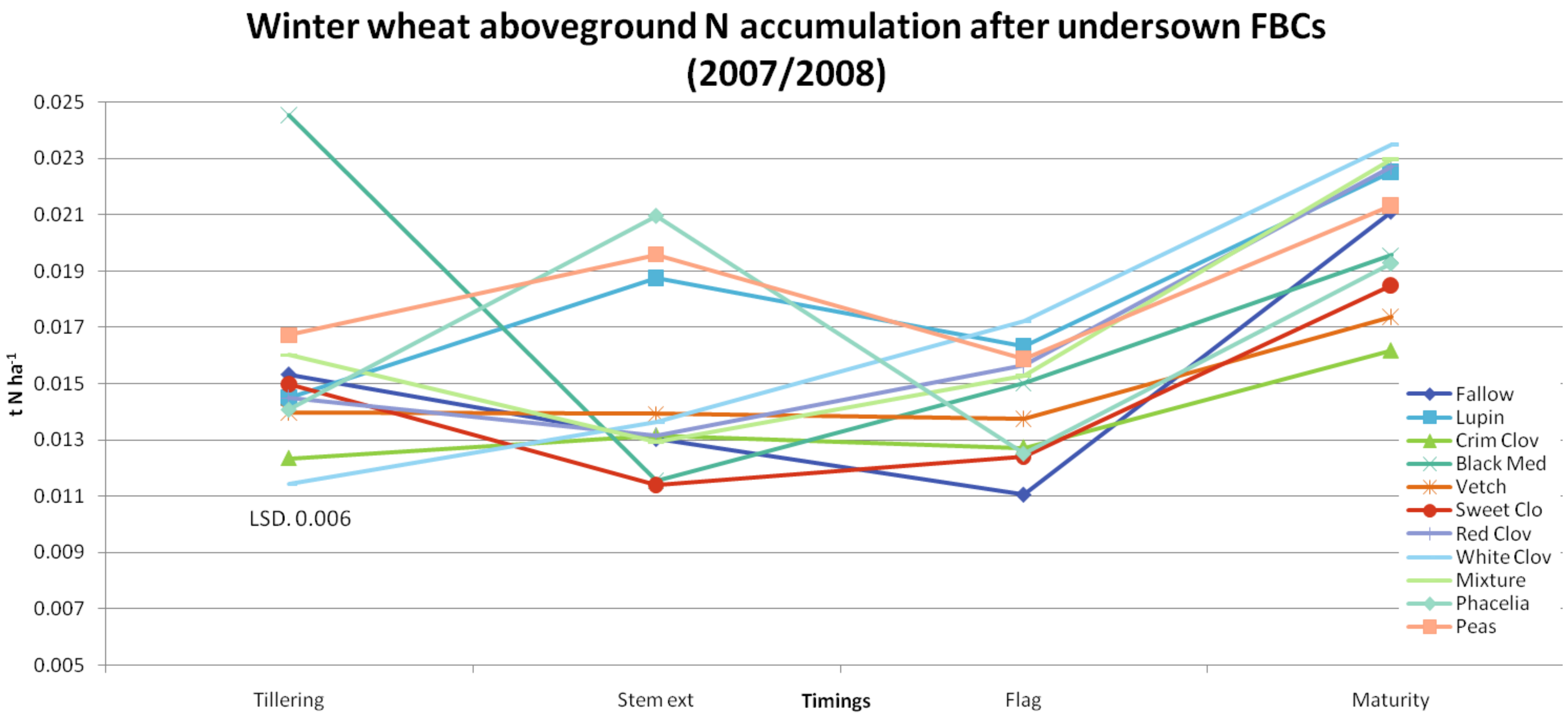


Figure 4.16 Winter wheat and weeds N accumulation after under sown FBCs

Meaned data sets, Repeated measures ANOVA analysis with Fishers protected multiple range test. Timings analysed by split plot ANOVA.

FBC species	M.S	df	P value	Timings	M.S	df	P value
Species	0.00005882	10	0 .142	Timings	0.0005387	3	<.001
Residual	0.00003747	53		Time x Species	0.00004585	30	0.123
				Residual	0.00003301	165	

N accumulation in above-ground residues (test crop + weeds) indicated significant accumulation changes over the growing season. Individual FBCs did not differ significantly in N accumulated at individual timings, with the exception of black medic at tillering.

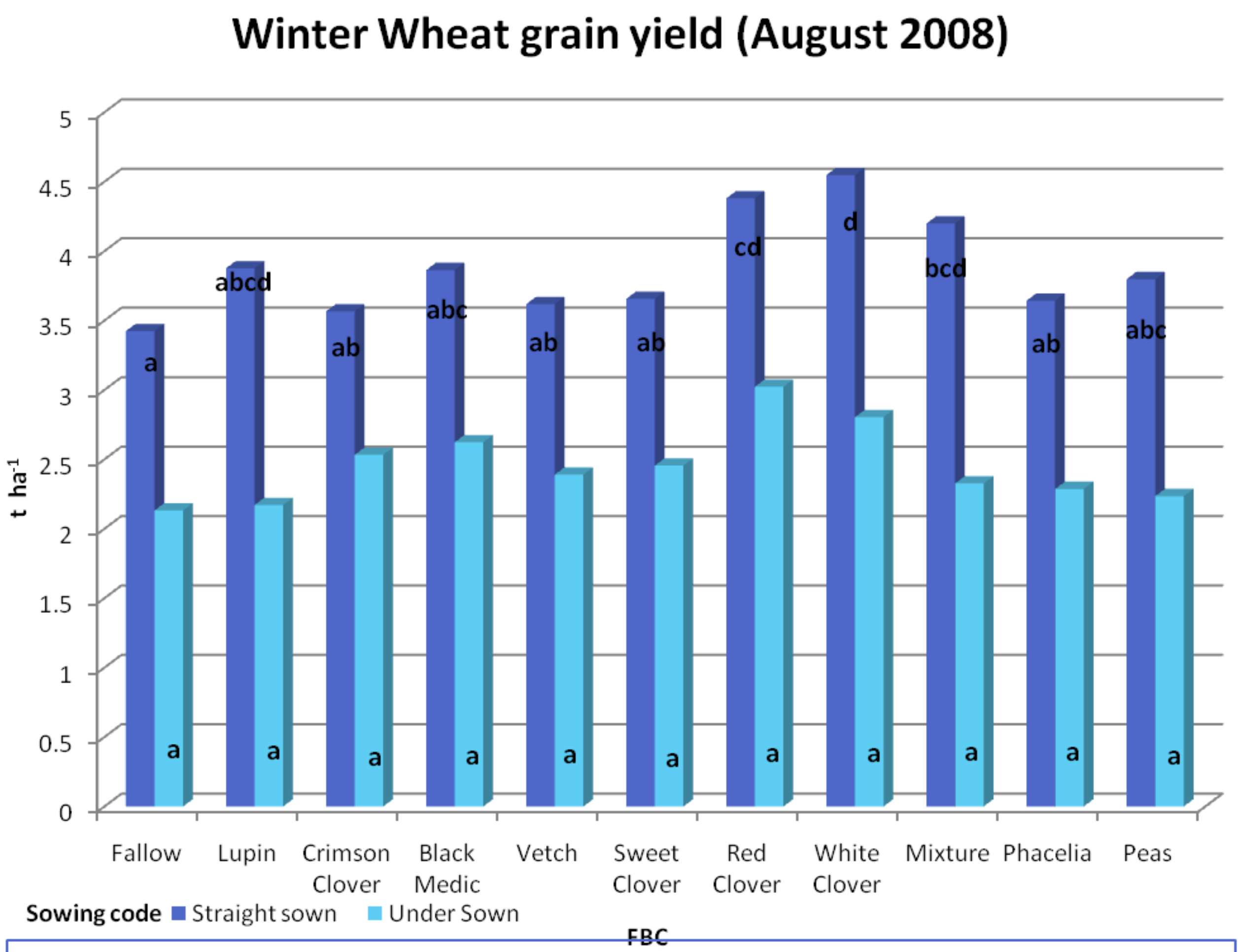


Figure 4.17 Winter wheat grain yield

Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars with the same letters are not significant different ($P<0.05$) Significant sowing code interaction ($P<0.001$), no significantly species sowing code interaction

FBC species SS	M.S	df	P value	FBC species US	M.S	df	P value
Species	0.3855	10	0.012	Species	0.2284	10	0.383
Residual	0.1562	20		Residual	0.2005	20	

Winter wheat grown after straight sown FBCs significantly ($P<0.001$) outperformed their undersown counterparts (averages 3.87t ha^{-1}; 2.45t ha^{-1} respectively). There were no significant differences in wheat yields grown after undersown FBCs. Winter wheat grown after straight sown FBCs demonstrated significant differences ($P<0.05$) in grain yield with perennial and grain legumes and the mixture demonstrating superior levels.

Figure 4.18 - Relationship between winter wheat flag leaf N accumulation and grain yield

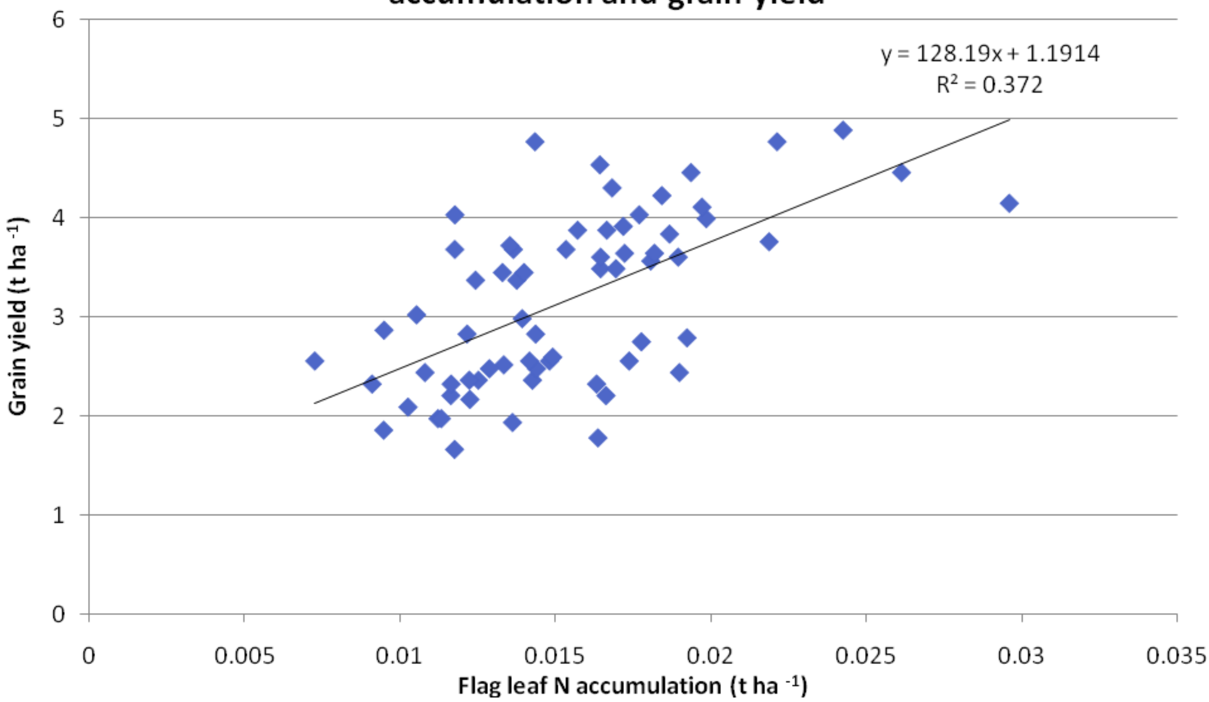


Figure 4.18 indicates a significant ($P<0.003$) relationship between vegetation N levels at flag leaf emergence and grain yield. 37.2% of the variation in grain yield (t ha $^{-1}$) was attributed to N levels in above-ground vegetation at flag leaf emergence.

4.4.3 Performance of spring wheat test crop

4.4.3.1 Soil monitoring

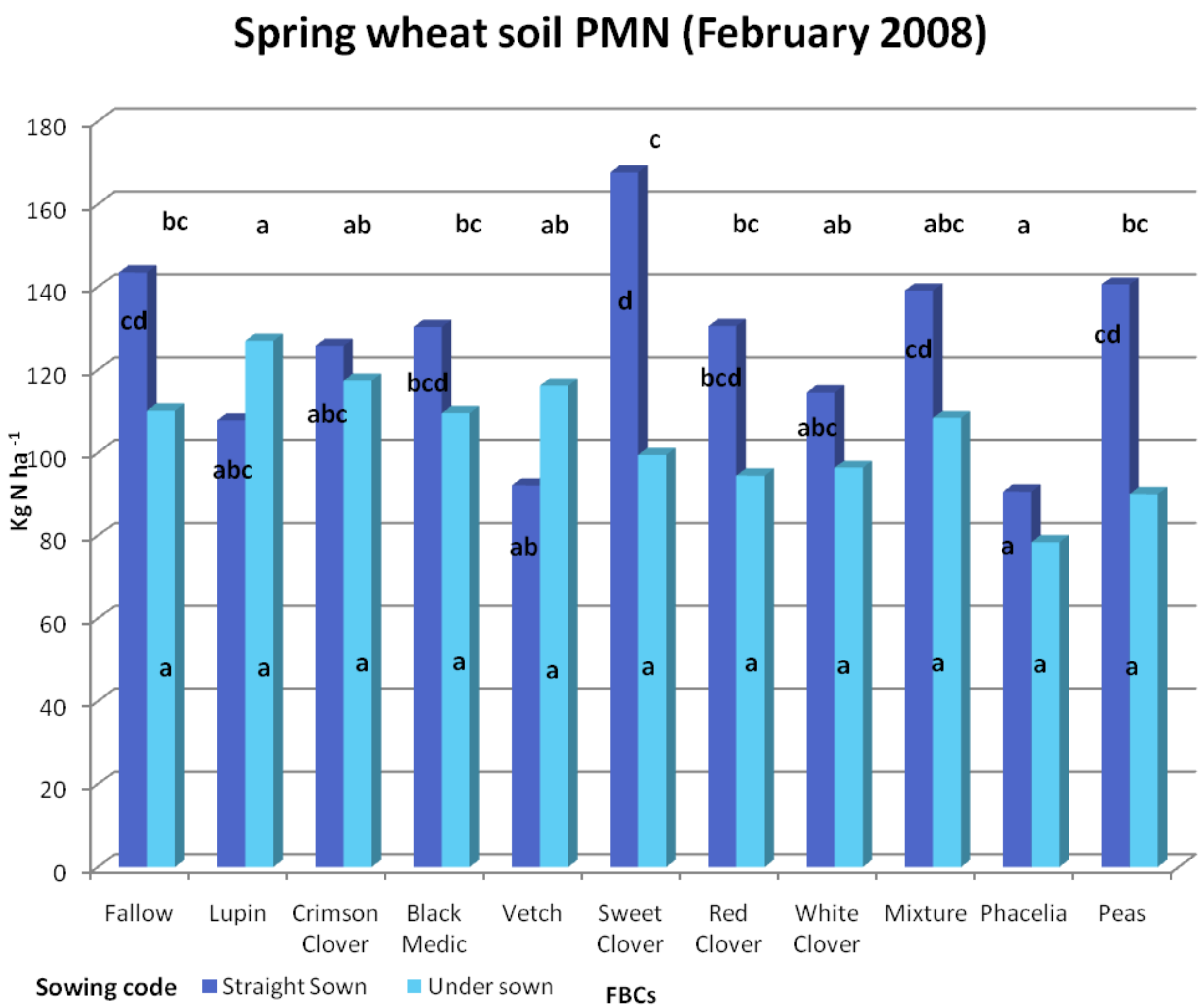


Figure 4.19 Spring Wheat PMN February 2008

Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars and pairs of bars with the same letters are not significantly different (P<0.05).

FBC Straight sown	M.S	df	P value	FBC interaction	M.S	df	P value
Species	3198.0	10	0.009	Species	2659.0	10	0.014
Residual	623.57	53		Sowing code	15047.0	1	<0.001
				Species x Sowing code	1729.0	10	0.135
				Residual	1123.0	108	

Soil PMN values at the commencement of the spring wheat test cropping phase indicated significant differences between FBCs across the sowing regimes (125.7; 104.3kg N ha^{-1} straight sown v. undersown) and within the straight sown treatments.

FBCs with the highest levels of soil PMN were fallow, black medic (*M. lupulina*), sweet clover (*M. officinalis*), red clover (*T. pratense*), the mixture and peas (*P. sativum*). Only black medic (*M. lupulina*) and the mixture had overwintered successfully.

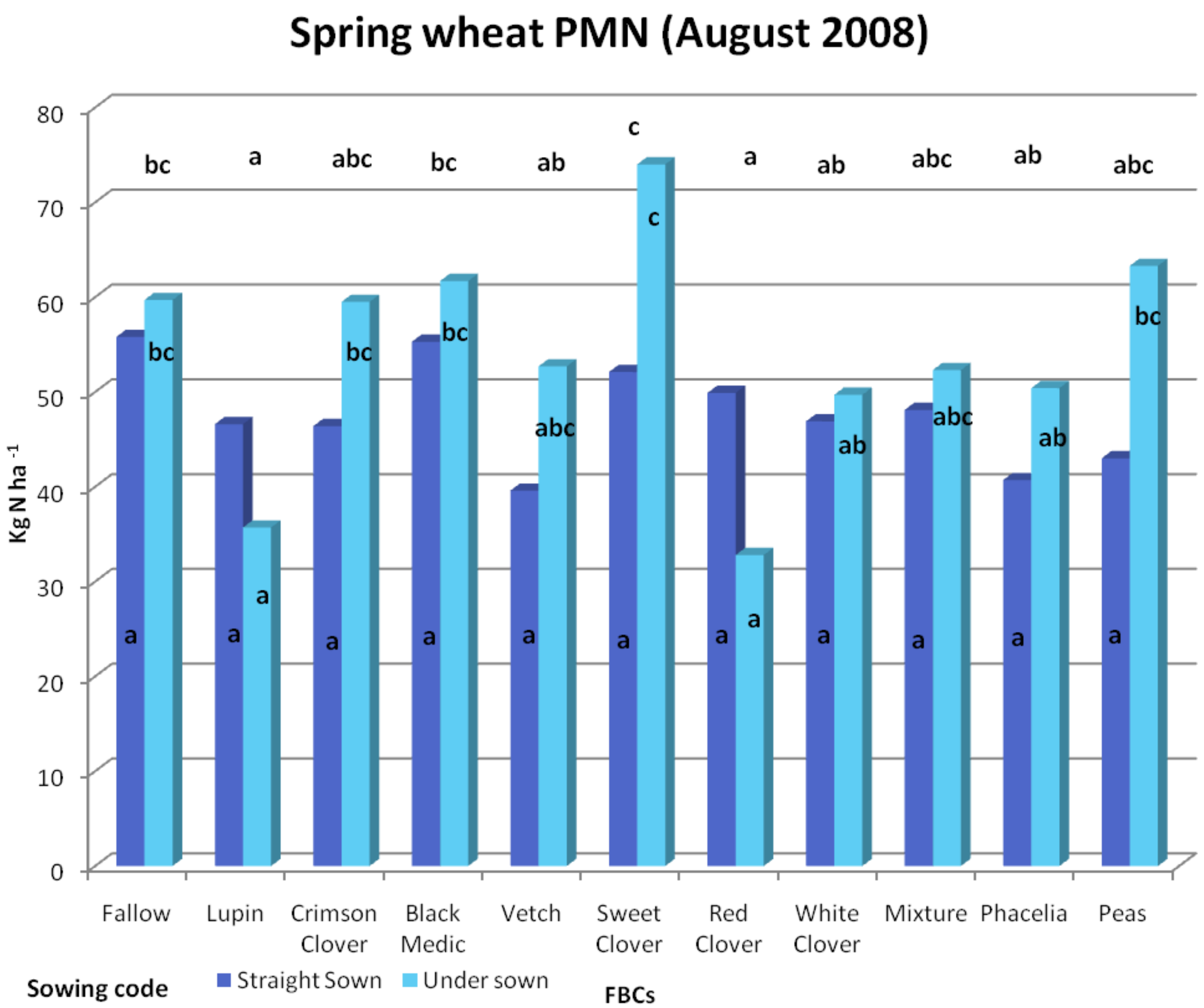


Figure 4.20 Spring Wheat PMN August 2008
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars with the same letter are not significantly different (p=0.05).

FBC Under sown	M.S	df	P value	FBC interaction	M.S	df	P value
Species	858.0	10	0.023	Species	609.0	10	0.045
Residual	336.2	53		Sowing code	1239.5	1	0.049
				Species x Sowing code	422.9	10	0.210
				Residual	311.4	108	

Samples were taken at the conclusion of the spring wheat test cropping phase, levels of PMN are likely to influence the subsequent cropping. Soil PMN values varied significantly ($P<0.05$) between FBC across the sowing codes. The straight sown PMN levels were significantly ($P<0.05$) lower than the undersown (47.7; 53.8kg N ha^{-1} respectively).

4.4.3.2 Vegetation monitoring

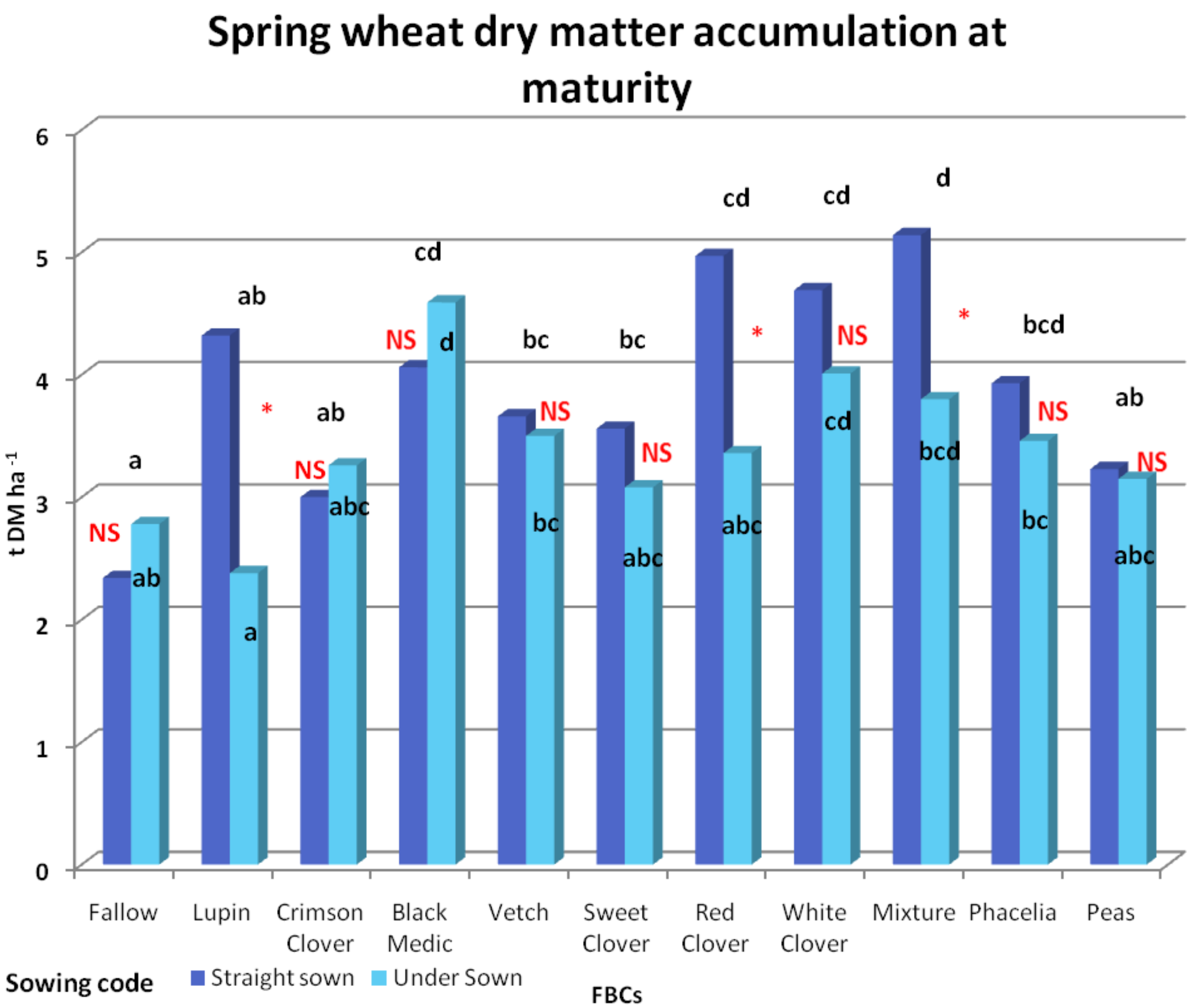


Figure 4.21 Spring Wheat DM accumulation at maturity
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars with the same letters are not significant different ($P<0.05$).Pairs of bars labelled * ($P<0.05$) or NS indicates the significance of the interaction between sowing code and spring wheat DM yield.

FBC Straight sown	M.S	df	P	FBC species	M.S	df	P value
Species	4.444	10	<0.001	Species	4.523	10	<0.001
Residual	1.249	53		Sowing code	8.339	1	0.005
FBC Under sown	**M.S**	**df**	**P**	Species x Sowing code	2.066	10	0.039
Species	2.1450	10	<0.011				
Residual	0.8163	53		Residual	1.027	108	

Spring wheat above-ground DM yield (t ha^{-1}) varied significantly across and between the sowing regimes. After straight sown FBCs highly significant ($P<0.001$) differences occurred with natural fallow regeneration, crimson clover (*T. incarnatum*), sweet clover (*M. officinalis*) and peas (*P. sativum*) exhibiting the lowest levels. The highest DM yields occurred after perennial legumes, the mixture, *Phacelia* and white lupin (*L. alba*). A similar DM accumulation pattern was seen after undersown FBCs with the lowest yield levels being expressed by the same FBCs as the straight sown plus lupin (*L. alba*) and red clover (*T. pratense*). The highest yielding spring wheat crops after undersown FBCs were after black medic (*M. lupulina*), white clover (*T. repens*) and the mixture.

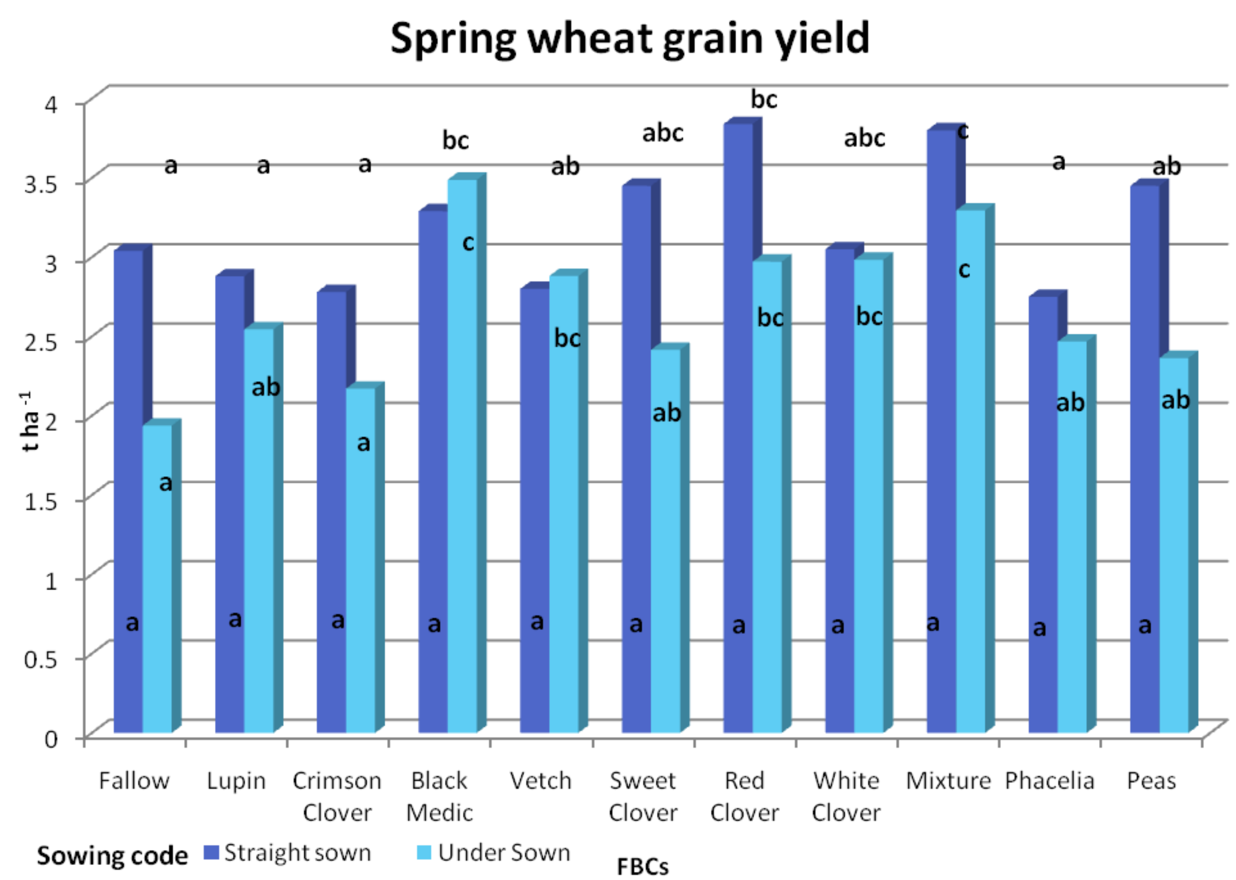


Figure 4.22 Spring wheat grain yield
Meaned data sets, ANOVA analysis with Fishers protected multiple range test. Bars and pairs of bars with the same letters are not significantly different (P<0.05.).

FBC Under sown	M.S	df	P value	FBC species	M.S	df	P value
Species	0.6876	10	0.002	Species	0.8319	10	0.008
Residual	0.1522	20		Sowing code	4.2874	1	<0.001
				Species x Sowing code	0.3311	10	0.357
				Residual	0.2904	42	

Spring Wheat grain yield differed significantly ($P<0.001$) between the sowing regimes with straight sown yielding 3.19t ha^{-1} and undersown 2.68 t ha^{-1}. Spring wheat after undersown FBCs demonstrated significant ($P<0.01$) differences in grain yield with perennials (*M. lupulina, T. repens, T. pratense*), the mixture and vetch (*V. villosa*) having the highest grain yield, with a range of 2.881 -3.488t ha^{-1}. FBCs exhibited significant ($P<0.01$) differences in grain yield irrespective of the sowing regime, all crops were comparable with the exception of the perennial legumes, the mixture and sweet clover (*M. officinalis*).

4.5 Discussion

The objective of this trial was to investigate and measure the N contribution of a range of short term legume and non-legume FBCs, established by straight sowing or undersowing, and their effects upon subsequent winter and spring wheat test crops.

The choice of FBCs detailed at the beginning of this chapter was designed to offer a wide range of residue quantities and qualities and to be reasonably compatible with the site and soil type (See chapter 3 and 4.1.1). Details of the criteria for selection were given in the opening sections of this chapter. However it is important here to note the nature of the “fallow” treatments as previously described. “Undersown fallow” in effect, constituted a “do nothing” control to set against all the other FBC treatments.

It is important also to realise the reasons for the choice of establishment methods (also referred to in the ANOVA tables as “sowing codes”). Several authors (Tonitto *et al.,* 2006; Fageria, 2007) have questioned the use of FBCs on economic grounds because of the loss of cash cropping potential during the period of growth of the FBC. Undersowing in a spring cereal may help to reduce this disadvantage but introduces other factors such as the effect of the FBC on the yield of the cover crop (e.g. Breland, 1996b) as well as the possible effects on the efficacy of the FBC. In the case of this field trial however, the yields of spring barley were not affected by undersowing any of the FBCs (Fig. 4.7). Bergkvist *et al.,* (2011) undersowed red and white clover in winter wheat and found little effect on the yield of the cover crop.

There remains the need also to consider the effect of undersowing on the efficacy of the FBCs. All FBCs established well in the spring of 2007. Sowing rates were the same for both establishment methods. Fig. 4.1 shows significantly ($P<0.001$) lower FBC plant populations for the undersown treatments compared to straight sown (average 106.9 v 167.0 plants m^{-2} respectively). Plant populations of sweet clover, red clover and white clover were all significantly ($P<0.001$) reduced by undersowing. Straight sowing in the autumn of 2007 (on 24th September after a protracted and very wet harvest period) was unsuccessful and the treatments were later abandoned. The undersown FBCs had much lower DM yields than straight sown and consequently lower N yields per hectare (Figs 4.5 – 4.8). Weed DM yields too were also substantially reduced by undersowing (Fig 4.2). In spite of some promising data concerning the PMN levels in soil under the winter wheat test crop (Fig 4.11) in the final assessment of grain yield (Fig 4.17) the undersown treatments on average yielded 1.42 t ha^{-1} of grain less than the straight sown ($P<0.001$).

Synchronisation is critical to successful FBC utilisation, Korsaeth *et al.,* (2002) and Fychan *et al.,* (2006) studies indicated spring test cropping to be advantageous over autumn, whereas Thorup – Kristensen (1996) indicated that spring incorporation delayed net N mineralisation, and was subsequently too late for successful crop utilisation. Overwintered FBCs were incorporated in February 2008 and spring test cropping established in March 2008. The data for the spring wheat test crop is less complete than that for winter wheat and because of pressures on laboratory facilities, and time constraints, samples for PMN were taken only in February and August 2008. In February (Fig. 4.19) the straight sown FBC plots contained on average about 21kg N ha^{-1} more than the undersown. However, by August (Fig. 4.20) this situation had reversed to some extent and the plots after the undersown FBCs contained slightly more N. This was probably a result of the higher C:N ratios of the undersown FBCs which included some barley stubble residues. Spring wheat sown after straight sown FBCs yielded on average 0.51 t ha^{-1} more than when grown after the undersown treatments ($P<0.001$ Fig 4.22). However, it was very interesting to note the significant ($P<0.002$) differences between the undersown treatments where the black medic, vetch, red and white clovers and the mixture FBCs all produced substantial yield benefits compared with the “undersown fallow” treatment (i.e. spring wheat following non-undersown spring barley).

One of the key features if FBCs are to be economically attractive is weed suppression, a desirable trait in commercial agriculture (Fageria, 2007). Because of the diverse nature of the FBCs and their various susceptibilities no blanket herbicide treatment of either straight sown or undersown FBCs was possible during the fertility accumulation period. This provided an opportunity to examine the true ability of an FBC to suppress weeds and it was interesting to note also crop / weed associations and the differences in weed flora which established, particularly in the straight sown FBCs. These are depicted in figures 4.5, and 4.6. It was notable that in most cases undersowing substantially and significantly reduced weed ingression. *Phacelia* was particularly competitive with weeds and levels of ingression in both straight sown and undersown plots were low. This probably reflected the crop removing labile N from the soil profile, thus creating a less satisfactory environment for weed development.

Plates 4.6 and 4.7show *Phacelia* weed cover between the two establishment systems.

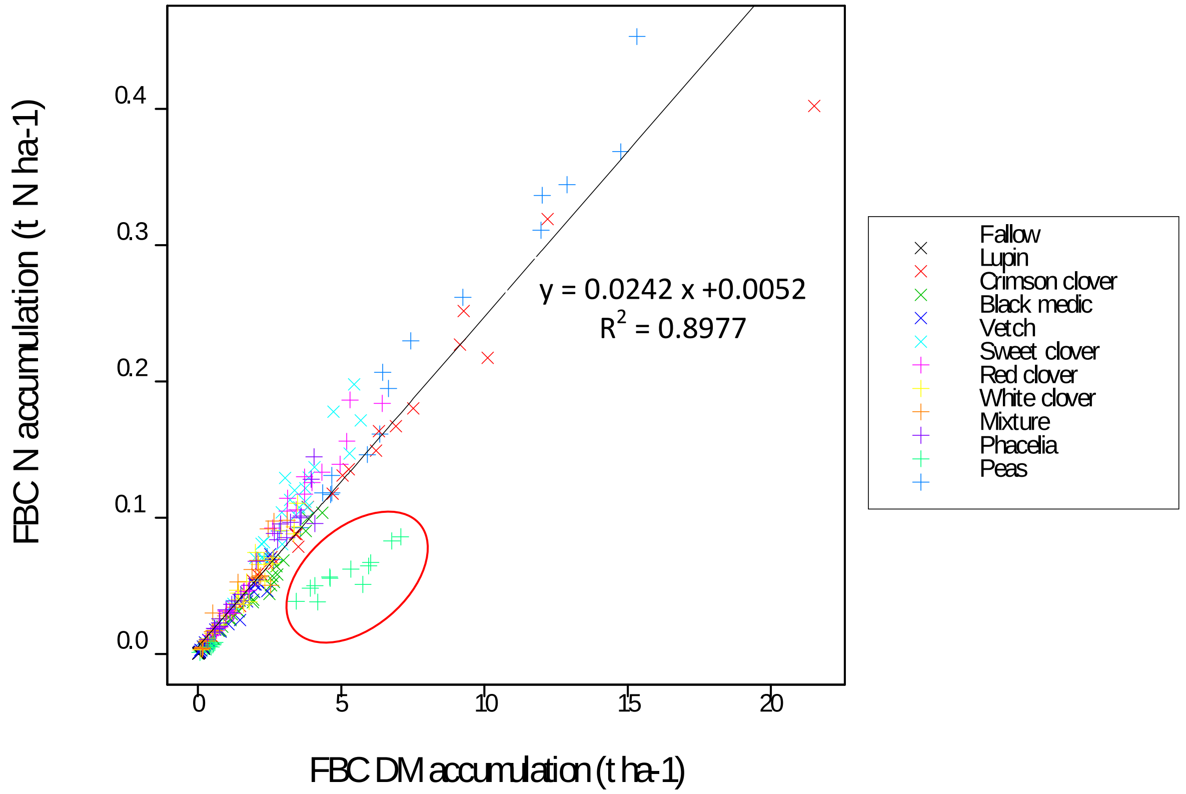
Plate 4.6 *Phacelia* undersown

Plate 4.7 *Phacelia* straight sown

A fundamental criterion identified by Fageria (2007) is for FBCs to produce sufficient DM to ameliorate any soil physical, chemical or biological impacts. When N is removed from the soil profile and not converted to plant tissue in sufficient quantity this can cause pre – emptive competition and subsequent N deficiency for the following crop (Thorup-Kristensen, 2003). On this basis the study of Angus *et al*., (2000) indicated a preference for annual FBC species over perennial. In this field trial the highest above-ground DM yields were expressed by the annuals, white lupin, peas and vetch and the biennial sweet clover (Figs 4.5 and 4.7, see also table 3.17). Annuals had the highest yield potential in the short term (4 month) cropping window, although perennials regenerated after summer mulching. The greatest levels of biomass production over the winter period were produced by the perennials (black medic, white clover and the mixture) and *Phacelia*.

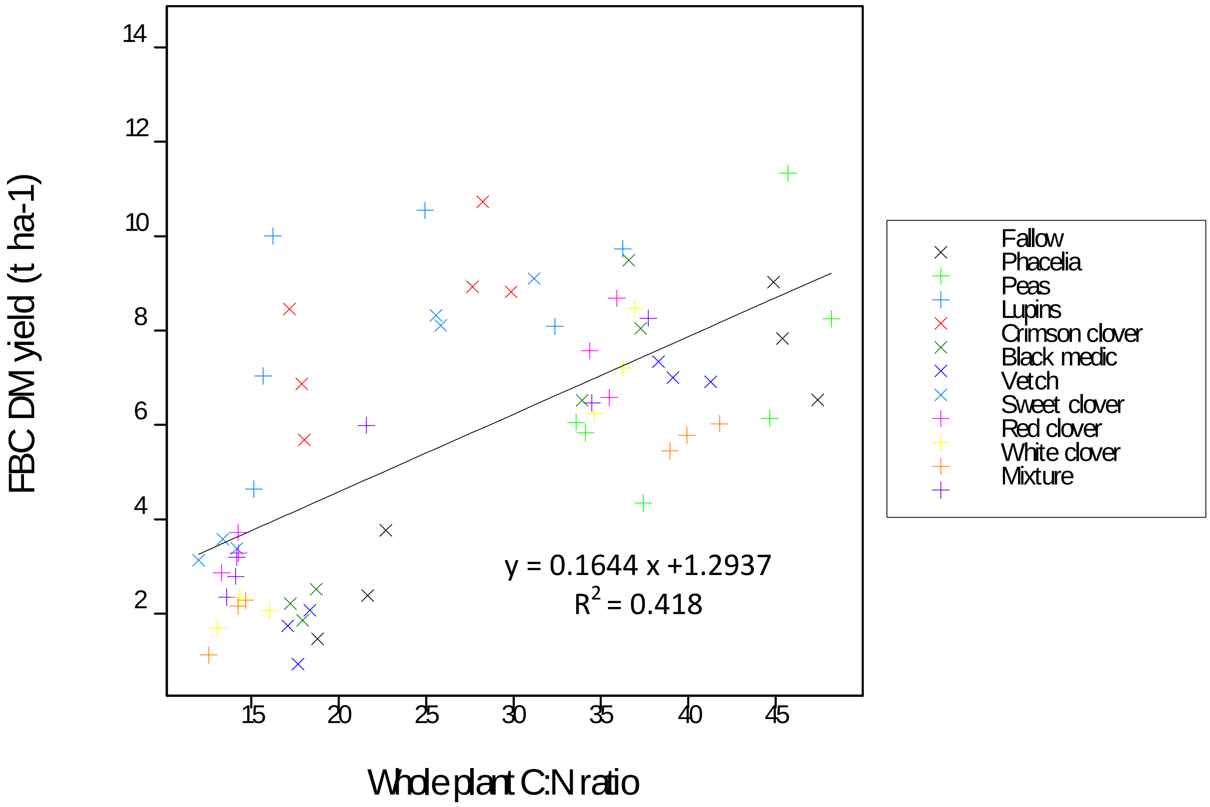
The fundamental relationship between DM yield and N accumulation is well documented within the literature. The studies of Tonitto *et al*., (2006) and Cherr *et al.,* (2006) showed that FBC yield performance was critical to N accumulations and to the yield of the following crop. This relationship was due to the positive correlation between BNF and the quantity of DM produced and subsequent N accumulation (Chalk and Ladha 1999; Unkovich and Pate 2000; Cuttle and Goodlass 2004).
Fig.4.23 indicates the highly significant relationship between straight sown FBC above-ground DM yields and N accumulation (R^2 = 0.90). The perennial species had higher N %s but lower DM yields and consequently lower N yields per hectare. The accumulation of N was therefore strongly correlated with FBC DM yield. The exception was the non-legume *Phacelia* which accumulated substantial levels of DM with a low N percentage and subsequently a low total N yield (circled on the Fig 4.23). The mixture FBC treatment in the Coates Manor Farm situation accumulated significantly ($P<0.05$) higher levels of DM and N than all its constituent parts with the exception of sweet clover, and when undersown the mixture significantly outperformed all its constituents. HØgh-Jensen and Schjoerring (2001) and Bergtold *et al.,* (2005) also found an increase in N fixation from a legume mixture. It was inferred by these authors that the increased competition induced more aggressive nodulation.

Figure 4.23 Relationship between FBCs (actual data used is straight sown and undersown FBCs + weeds) DM yields and N accumulation based on the yields recorded in August 2007 see also Fig. 4.6



Nitrogen release from residues and uptake by a following crop is however not only dependent on the quantities of N interred but on the quality of the residues as expressed by their C:N ratios (as explained in 4.1.2) (Vahdat *et al.,* 2011). Residue quality is extensively referred to in the literature as being the critical determinant for residue behaviour once incorporated (Lupwayi *et al.,* 2006; Fageria, 2007; Kumar and Goh, 2002). Of the available indices for residue quality C:N ratio is the most extensively used (Kuo and Jellum, 2000). The diverse genera and botanical morphology of the featured FBCs is reflected in the diversity of their C:N ratios (range 10.6-36.6:1) (Table 3.1). The closest estimate to the residue quality of the actual interred material was whole plant (FBC + weed) C:N ratio. The relationship between FBC yield and C:N ratio is depicted in figure 4.24.

Figure. 4.24 Relationship between FBC DM yield and whole plant C:N ratio



The data obtained from the literature, from the pot experiment described in chapter 3 and from the harvests in the autumn of 2007 from the field trial described in this chapter, suggest the categories set out in table 1 for "whole plants".

Table 4.9 Summary of FBCs quality characteristics

C:N ratio	Whole plant N content %		
	High 3.0 % +	**Medium 2.0 – 3.0 %**	**Low <2.0 %**
High >20			*Phacelia* *Fallow*
Med 15 – 20		*White lupin* *Peas* *Crimson clover* *Black medic*	
Low <15	*Vetch* *Sweet clover* *Red clover* *White clover* *Mixture*		

N content has been identified as a key determinant to N mineralisation (Vahdat *et al.,* 2011; Jensen *et al.,* 2005) and the highest FBCs N% (table 4.9) also feature in the highest levels of potential mineralisation (table 4.5). Legume FBCs vetch, the perennials and sweet clover consistently expressed significantly ($P<0.05$) lower C:N ratios than pea and white lupin (table 4.4). C: N ratios below the balance point are consistent with the literature (Briggs, 2007; data in Fageria, 2007), however the vetch data from this trial was more consistent with vegetative rather than pod set stage (Fageria, 2007). Fox *et al.,* (1990) indicated annual / short term crops have relatively low lignification levels. The mixture had a low C:N ratio, confirming results from Clark *et al.,* (1994) and Mutch and Snapp, (2003) that the interaction of different species enhances the soluble C and N contents.

Sweet clover has a high N content and a low C:N ratio. However, potential mineralisation levels were the lowest over the sampling period. This is consistent with the findings of Brandsæter *et al.,* (2008). The literature also indicates that lignin levels can govern residue behaviour and that sweet clover has a higher content than red clover and vetch (Vahdat *et al.,* 2011; Nordkvist *et al.,* 1989; Lithourgidis *et al.,* 2006).

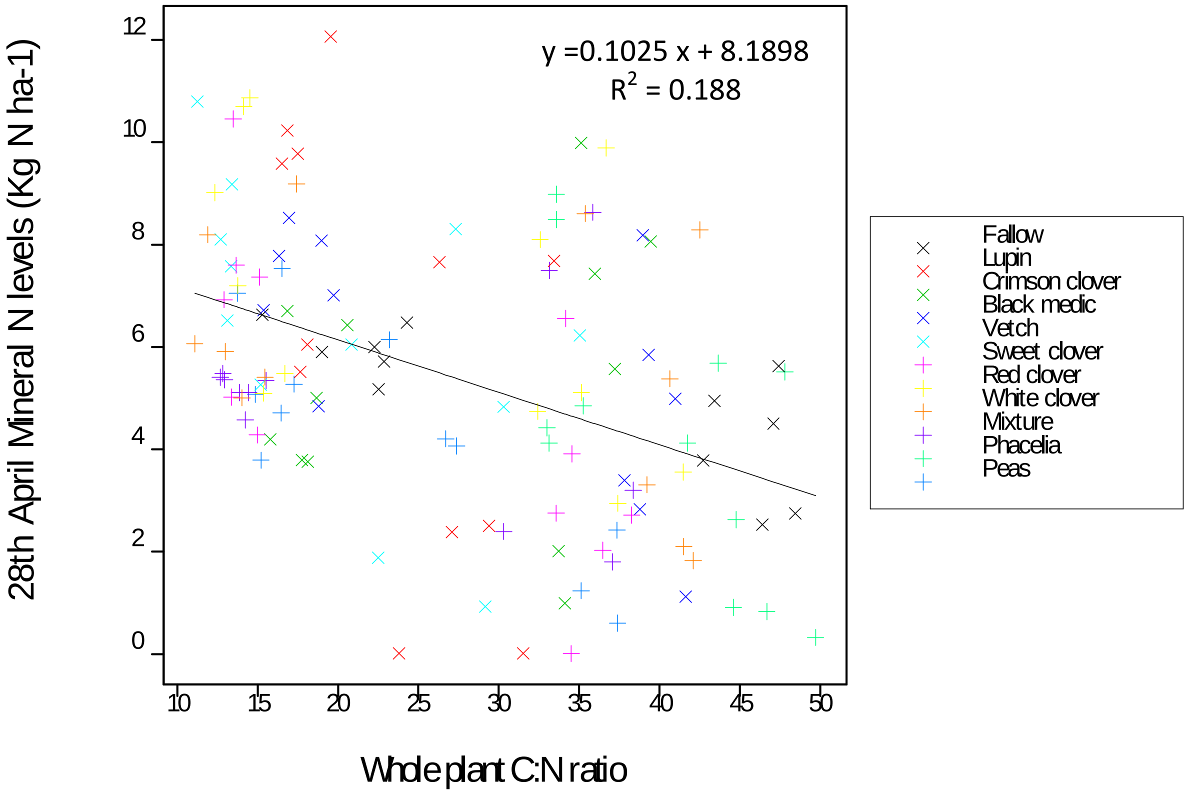
Fallow and *Phacelia* across both sowing regimes (with the exception of the overwintered *Phacelia*) and undersown FBCs (due to the interred barley stubble material) gave the widest C:N ratios, well above the balance point. Dinnes *et al.,* (2002) found that C;N ratios above 20 induced temporary immobilisation for 2 weeks. White clover and black medic both increased C:N ratios after overwintering which represented an increase in maturity (Table 4.4). Sweet clover did not overwinter successfully, and this probably resulted in the reduction in C:N ratio shown by the mixture in the spring. The overwintered *Phacelia* had a low C:N ratio because it was very immature having regenerated from shed seed. It was notable that the PMN levels measured in August 2008 in the spring wheat test crop showed increased PMN levels from the undersown residues (with higher C:N ratios) compared with the straight sown indicating a delay in N mineralisation.

Various authors have attributed rapid mineralisation with low C:N ratios. Varco *et al.,* (1989) found that vetch released within just 15 days post incorporation. However, general indications are that most FBCs release over a period of several months (Breland, 1994; Throup – Kristensen *et al.,* 2003). Ladd *et al.,* (1981) reported that under field conditions even low C:N ratio crops may only mineralise 10-20% of N content. Short term temporary immobilisation may not hamper test crop development however, as annual crops require pulses of nutrition at key times throughout the growing season (Tonitto *et al.,* 2006; RB209 DEFRA 2010). Rapid mineralisation may be problematic if test crops are unable to utilise all the available N (Korseath *et al.,* 2002). In essence synchronicity is critical between FBC release and subsequent crop uptake (Tonitto *et al.,* 2006; Korseath *et al.,* 2002).

High levels of potentially available N were observed as a result of the PMN assessments, but also very low levels of SMN within the profile at specific sampling times (see also chapter 5). This was probably due to the winter wheat test crop taking up most of the available N. However, Vigil and Kissel (1995) suggested that C:N ratio poorly estimates N mineralisation in a range of 10-28 and Ladd *et al.,* (1981) suggested that field conditions may modify residue behaviour. In this study autumn 2007 SOC accounted for 17.7, 16.2 and 24% of the variance in SMN levels in December, February and April indicating that early test crop nutrition was in part being supplied by the native soil organic sources.

The relationship between PMN levels after FBC incorporation and residue C:N ratios within this trial was poor. A more significant relationship occurred between, SMN levels and whole plant C:N ratios (18.8% of variance on 28th April). Furthermore, N levels in winter wheat in November after undersown black medic were significantly ($P<0.001$) higher than all other FBCs (except red clover) in tillering test crop biomass (Fig. 4.16).

Figure 4.25 Relationship between whole plant C:N ratio and mineral N levels on April 28th .



FBCs and establishment methods significantly (P<0.001 and 0.013) influenced PMN levels for the whole season for the winter wheat test crops. The undersown levels were on average only 6.96Kg Nha^{-1} lower over the cropping season. However straight sown PMN levels were sustained at a high level from November until the end of April, whereas levels after undersown FBCs peaked in December and January. Significant differences in levels between sowing regimes occurred at key winter wheat developmental timings (November, December, January, February, 28th April and May) and are likely to have resulted in the highly significant (P<0.001) differences in winter wheat grain yields between the straight sown and undersown sowing regimes (Fig. 4.17).

Although no direct relationship was detected between season PMN levels and winter wheat grain yield, PMN levels significantly (P<0.014) influenced N accumulation in winter wheat biomass (see also Fig. 4.15) and the influence of specific FBCs was evident at winter wheat stem extension (G.S.32) (Fig. 4.14) where straight sown red and white clovers and the mixture gave significant improvements in GAI compared to most other FBCs.

The relationship between vegetative growth and grain yield is demonstrated is demonstrated most significantly with flag leaf N levels (R^2=0.372) (Fig. 4.18). The highest ($P<0.05$) test crop N recovery in biomass was from the red clover and white clover treatments (Fig. 3.20).

Undersown FBCs resulted in significantly lower ($P<0.001$) PMN levels (Table 4.6), lower N accumulation ($P<0.001$) (Figs 4.15 and 4.16) and lower test crop DM biomass yields ($P<0.001$) (appendices 3.2.3.8 and 3.2.3.9). Undersown FBCs also resulted in significantly ($P<0.001$) lower grain yields (Fig. 4.17) and N offtake (appendix 3.2.3.11) in grain.

There were no significant differences in winter wheat grain yields between undersown FBC treatments whereas wheat after straight sown FBCs demonstrated significant ($P<0.05$) differences with red and white clovers and the mixture outyielding the “control” (i.e.”undersown” fallow) by more than 2 t ha^{-1} (Fig. 4.17). At a feed wheat price of around £150 per tonne this represents a figure of about £300 which could be set against the opportunity cost of a 1 year straight sown FBC break prior to growing winter wheat.

4.6 Conclusions

Both winter and spring wheat test crops showed statistically significant grain yield increases as a result of the inclusion of short term FBCs in a cereal rotation. In both cases red and white clovers and the legume mixture gave the best results (with the addition of black medic and vetch in the case of spring wheat) when compared with the option of non-undersown spring barley followed by the test crops. In the case of winter wheat, straight sown FBCs gave the best yields whereas for spring wheat, in spite of a higher average yield from straight sown FBCs, an attractive option, appeared to be undersowing red or white clovers, the mixture, or black medic, in spring barley and following with spring wheat.

Chapter 5, Modelling

The data and experiences described in chapters 3 and 4 relate to the specific circumstances of crops grown on land near Cirencester, UK, in 2007 and 2008. This chapter contains a description of the attributes of a range of computer models and an account of the use of the data in testing and further developing the predictive qualities of a simple model dealing with the accumulation and recovery of N in a mixed arable farming system.

Efficient N utilisation by crops is affected by a combination of the availability of SON, and the accumulation of N by FBCs, as well as the inorganic N applied as fertiliser. This may be further complicated by agronomic practices and weather conditions, making precise predictions difficult (Korsaeth *et al.,* 2002). Modelling provides a chance to integrate all these factors. Modelling of N fixation, accumulation and recovery has been previously studied by Jørgensen and Ledgard (1997) (simple fixation model) Hansen *et al*., (1991) (the DAISY mechanistic simulation model, focusing on N supply and simulating soil residue interactions) and Wu and McGechan (1999) (SOILN, a soil N dynamic model). Models have varying degrees of applicability to commercial agriculture due either to requirements for extensive parameterisation or to the over-simplification of complex systems to make them “farmer friendly”.

5.1 Accumulation Models

The literature indicates a correlation between legume crop yield and N fixation (Heuwinkel and Locher 2000; Kumar and Goh, 2000; Loges et al, 2000). This association suggests crop yield as being a good parameter for modelling N fixation, with the potential to become the basis of a simple commercially adoptable method for a field situation. Models utilising this correlation have been produced by Vinther and Jensen (2000) and Bowman *et al.* (2002). Kristensen *et al.,* (1995) and Korsaeth and Eltun (2000) also utilised the easily available parameters of legume content, yield assessment and potential fixation figures to provide an estimate of fixation levels. Korsaeth and Eltun (2000) also incorporated a simple management corrective tool, whereby a 10% reduction in fixation levels was allocated for mulching.

There are indications that above-ground N accumulation is often different to below-ground levels (Kirchmann, 1988) with, reportedly, whole plant levels often underestimated. Early work by Hay *et al.,* (1985) and Caradus (1986) concluded that >50% of N was stored below cutting height. To account for this Jørgensen and Ledgard (1997) suggested a correction factor of 1.7 to be multiplied to the above-ground estimates to account for N below cutting height. Within their research with white clover (*T. repens*) the proportion of N yield in stolons and roots was 30%, 36% in stems and 34% in leaves.

These models rely on a constant correlation between % Nitrogen derived from the atmosphere (%Ndfa) and N concentration in plant on the basis of soil N content. However the literature (Cuttle *et al.,* 2003) indicates that %Ndfa varies due to soil, climatic and managerial influences. A model demonstrating extensions of this has been produced by Wheeler *et al.* (1997) with the inclusion of simple meteorological data. However, to be able to provide an accurate estimate of N fixation more parameters would be required to mediate the site specific nature of the field situation.

More complex models including more variables and producing more reliable conclusions, have been demonstrated by Väisänen *et al*. (2000) and Spatz and Benz (2001). These often involve SMN measurements which are not widely used by the majority of commercial farms. Watson *et al.,* (2002) concluded that an N fixation model for a grass/legume ley required the following parameters:

- % legume in mixture
- Years after establishment
- N content of legumes
- N content of legumes plus grass
- N content of grass – only reference crop
- % legume N derived from fixation
- Correction for fixed N in stubble and roots

- Details of sward management.

Thus it can be seen that many factors affect N fixation and the quantities accumulated by FBCs. Representing all factors within models is very difficult and there is a need for advisory models to be simple to aid commercial utilisation, whilst being sufficiently comprehensive not to compromise on their accuracy.

5.2 N release models

Accumulation of atmospheric N fixation or the preferential uptake of mineral N by FBCs is only one element in supplying nutrition to subsequent crops. Both the subsequent release and availability of accumulated N can be subject to numerous influencing variables and these can be generalised as potential background soil mineral N levels governed by soil textural properties, climatic and managerial influences.

The properties of incorporated residues from FBCs may also influence nutrient release patterns, and crop uptake potential, efficiency and utilisation of mineral N may also vary. Losses from the soil system will also occur, influenced by natural cycling and managerial decisions. Fageria (2007) suggested that the essentials for N release quantification were the quantity of N and the C:N ratio of the residues and theoretical N partitioning between fast, medium and slow mineralising pools (Cuttle and Goodlass, 2004).

Models predicting N release follow in a similar vein to N fixation with simple or complex versions or soil tests. One modelling generalisation is a requirement to include a weather link due to the intrinsic relationship between mineralisation, temperature and soil moisture content, as demonstrated by the ADAS / DEFRA model MANNER. Modelling of mineralisation tends to be a more common method, because of the interaction of N mineralisation with potential N loss processes. These need to be modelled too, transforming the modelling to N supply rather than just mineralised N release. Models that involve simulating soil MIT processes have resulted in detailed complex studies. Examples include Standford and Smith (1972); Deans *et al.,* (1986); Parton *et al.,* (1987) and Whitmore (1996).

Paustian *et al.,* (1997) in a review indicated that such models needed to include functions such as temperature and moisture, to account for the growth dynamic of the microbial population with the inclusion of carbon-rich residues. This is important because N mineralisation is a by-product of C mineralisation (Paustian *et al*., 1997). These models demand a high level of detail and extensive parameterisation if they are to run correctly. Generally the C dynamics are modelled fairly accurately, but they can still fail fully to capture N dynamics (Cuttle *et al.,* 2003) due to uncertainty of the quantities and states of N in the soil system, as well as the secondary processes of microbial and chemical mediation, altering the sink destinations (Cuttle *et al*., 2003).

5.2.1 Review of N release models

Wu and McGechan's (1999) SOILN model is a soil N dynamic model and was adapted by Vold *et al.,* (1999) to create the SOILN-NO model. This model uses C and N transformation and transport in the soil-plant system. FASSET is a pasture based model, adapted by Berntsen *et al.,* (2005) to simulate the management effect on crop production, leaching, and fertilising effect post short term accumulation in a ley-based system. This is achieved by simulated daily changes in crop production, N uptake, temperature and the transport of solutes in the soil. DAISY was developed in Denmark by Hansen *et al.,* (1990; 1991) and is an extensively used model, examples are Müller *et al*., (2003) De Neergaard *et al.,* (2002) and Bruun and Jensen (2002) and validation examples include Hansen *et al.,* (1991); Smith *et al.,* (1997) and Jensen *et al.,* (1997) amongst many others. DAISY is a Soil-Plant-Atmosphere system model, designed within agro-ecosystems to simulate water, heat and solute balances and subsequent crop production under various management strategies. The main features of these three models are summarised in table 5.1.

Table 5.1 N release models descriptions

MODEL	Features	Advantages	Disadvantages
SOILN-NO Developed by Vold *et al.*, (1999)	C and N transformations, C mineralisation follows first order kinetics and N fluxes are proportional to C. Comprises two litter pools (rapid / slow decomposition), plus a stable humus pool and a microbial biomass and metabolites pool.	Korsaeth *et al.,* (2002) found the model simulated the N levels and N dynamics of white clover residues under spring barley in a field experiment very well. Model also successfully simulated the fluctuations in soil inorganic N over the season and between soil horizons (15cm increments) Korsaeth *et al.,* (2002)	Model was unable without modification to simulate a lag time between incorporation and mineralisation to reflect the input of stolons with a slow mortality rate (Korsaeth *et al.,* 2002).
FASSET Developed by Berntsen *et al.*, (2005)	Pasture based model. Simulates daily changes in crop production, N uptake, temperature and transport of solutes in the soil. Comprises two litter pools (rapid / slow decomposition), plus a longer term organic matter decomposition pool, as well as soil microbial biomass (SMB) and soil microbial residue (SMR) pools.	Provided accurate simulations of crop production after ploughing of a pasture (Berntsen *et al.,* 2006).	Pasture / ley based model not applicable to short term FBC simulations. No account taken of crop diseases within the simulations or of the inputs from roots and residues during growth (Berntsen *et al.,* 2006). To provide more reliable simulations, a recommendation exists for another SOM mixing pool with a half-life of 2-3 years (Berntsen *et al.*, 2006).

MODEL	Features	Advantages	Disadvantages
DAISY Developed by Hansen *et al.,* (1990;1991)	DAISY is a soil-plant-atmosphere system model. The soil nutrient simulations are via the MIT model. The MIT model comprises of at least two litter pools for added organic matter (rapid and slow decomposition), an SOM pool and an SMB pool. C transformations are subject to first order kinetics, with a constant C: N ratio and coefficients between pools controlling N mineralisation. Calibration of SOM pools is key to accurate simulations, which are a product of long term climatic and management practices (Bruun and Jensen, 2002; Hansen, n.d).	The model is designed to work within agro-ecosystems to simulate water, heat, solute balances and crop production under various management strategies. It is able to simulate root deposits, Farm Yard Manure (FYM), slurry, FBCs and residue inputs (Hansen, n.d) It has been re-calibrated with *Brassica napus* L. residues but is also applicable for cereal straw residues (Mueller *et al.,* 1997).	*Brassica napus* calibration may not be appropriate for residues with high metabolic components such as FBCs (Mueller *et al.,* 19998B), as demonstrated by De Neergaard's *et al.,* (2002) experiment. Unsatisfactory simulations of legume N mineralisation attributed in part to ineffective standard partitioning of residues into water soluble and insoluble fractions (Müller *et al* 2003; De Neergaard *et al.,* 2002). Fixed C:N ratio assuming constant substrate supply and constant turnover rate coefficient may not be appropriate since light particulate organic matter changes during decomposition (Magid *et al.,* 1997; Mueller *et al..,* 1997). In addition FBCs composition has been shown to mineralise rapidly independently of C, even at low temperatures (Magid *et al.,* 2001). Model assumes a constant decomposer community, however zymogenous microflora vary in their response to easily degradable plant materials in the short term (Bremer and van Kessel, 1992), whereas the model is calibrated on a long term study classical Rothamsted Model (Jenkinson *et al.,* 1987) No SMR pool, which may misrepresent N mineralisation as turnover of N may be temporarily incorporated into SMB and released later (Müller *et al.,* 2003).

MODEL	Features	Advantages	Disadvantages
FBC. Developed by Cuttle *et al.*, (2003)	A simple organic based rotation model, combining a ley fertility building phase with the capacity for 5 years subsequent cropping. Model simulates nitrogen mineralisation from the ley phase, residues and manure applications ultimately predicting N levels and crops yield (Cuttle, 2006). The stix model predicts the N mineralisation. This comprises of three litter pools, fast and slow pools follow zero order kinetics and first order reactions for the medium pool (Cuttle, 2006).	Simple farmer friendly interface, with easily obtainable information. This model has the ability to be ultilsed in conventional agriculture (Cuttle, S.P Pers. Comm). The model is able to include predictions from weed inputs. Farm specific rotational information, in combination with rainfall and soil texture descriptions may aid the accuracy of predictions.	Monthly timestep model may well be compromised on accuracy as compared to the daily timestep models such as DAISY, for example it can not simulate denitrification with monthly calculations and uses assumptions based on soil texture (Cuttle, 2006; Cuttle, S.P Pers. Comm). The model takes no account of crop diseases. The model currently does not have provision for many of the established FBCs as means of short term fertility building such as *T. repens* and *M. lupulina*, as well as no provision for undersown establishment.

5.3 FBC Model

The FBC model of Cuttle *et al.,* (2003) is a much simpler model than those discussed in the previous section and was originally designed to be applicable to an organic rotation where several years of ley are followed by several years (up to 5 years) of arable cropping. However the data from the study reported in chapter 4 was obtained from a conventional arable system partly because of the renewed interest in "green manure" FBCs highlighted by Fychan *et al.* (2006) and their wider commercial applicability. The model uses a Microsoft Excel spreadsheet - based with a farmer / adviser interface which comprises a simple series of look-up tables with readily available information.

The ley phase is not modelled specifically, but instead the model selects values for the amount of N accumulated by the ley from look-up tables appropriate to the type, age and management of the ley. Values are based on work by Whitehead *et al.,* (1990). The ley phase estimates set the parameters for the second phase of the model, which simulates the quantities of N mineralised from the ley and other crop residues during the rotation (Cuttle, 2006). Short term FBCs can be modelled within the rotation. Part of the proposed extension of the model is the inclusion of the broad range of FBCs featured in this research. The model currently features 24 crops with the ability for simulation of growing 2 crops / year (Cuttle, 2006).

The second, more detailed aspect of the modelling concerns the mineralisation of N following the incorporation of FBC residues. Cuttle [personal communication] has also indicated that "Full data are not available for all crops currently included in the model and estimates have been used for some parameters." So the data collated from this current research study will be used to try to validate some existing data sets and extend the remit of the model. The parameters required for simulation of the ley phase and FBCs are:

total weight of residues (kg ha^{-1});

and %N and %C in residues

These have all been gathered within this research project.

Climatic parameters are defined by region specific data (9 UK regions) accumulated from Met Office data from 1971-2000, with the exception of rainfall which can be entered as site specific information (in 50mm increments). Model soil information is based on RB209 (DEFRA, 2000 edition) soil classification, but with an additional category for sand to represent very low SOM and N content soils. Within the model the soil categories describe soil texture, depth of topsoil, inherent nutrient status and water characteristics.

The required inputs from farm records for successful model simulation are displayed in plate 5.1.

Plate 5.1 Example of the model input requirements

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(Cuttle, 2006)

5.3.1 Nitrogen mineralisation within the FBC model

Nitrogen mineralisation is based on the Stix model (J A King, ADAS, unpublished data) which simulates mineralisation from SOM and crop residues. This mineralisation model operates on a monthly time-step, and partitions residues (ley phase, crop residues or manure applications) into three decomposition pools (fast, medium and slow mineralisation rates) based on the incorporated materials' C:N ratios (Cuttle, 2006). The fast and slow pools proceed as zero-order reactions, whereas medium mineralisation rate pool is calculated as a first-order reaction. All of these reactions are temperature dependent (Cuttle, 2006). The monthly calculation for mineralisation levels provides an estimate of SMN available for plant growth (Cuttle, 2006).

5.3.2 Crop growth, N uptake and losses.

Crop growth is simulated by a simple model, which calculates the potential biomass production during each month based on climatic conditions (temperature, solar radiation and soil moisture), and crop-specific growth parameters. The model then compares the N required to achieve the potential biomass production, and that available from the mineralisation model. The arable crop parameters required for simulation, such as degree days to emergence, minimum air temperature for growth, leaf area index, radiation use efficiency and harvest data (yield, % DM and %N) are available or can be obtained from sources such as Korsaeth and Eltun (2000). Any SMN available post crop uptake is then available for leaching or denitrification. Within the model N may be eligible for leaching losses when rainfall exceeds evaporation and/or the profile is saturated. The fraction which is mobile and eligible for transport through layers of soil (5cm increments) is soil texture dependent. Denitrification simulations are not possible with monthly time step modelling. However, the proposed model does provide an estimate based on an assumed potential denitrification rate, and is governed by soil texture and mediated by SMN content and temperature (Cuttle, 2006).

Growth continues in monthly time steps until senescence or harvest, as determined by the SMN levels and crop growth boundaries. At harvest the crop N is partitioned between top crop (grain), straw / stubble and roots. Any interred material forms a fresh residue pool and is subject to partition into the three decomposition rate pools. Biological fixation from leguminous crops (Korsaeth and Eltun, 2000), weed levels and manure applications are incorporated into the model simulations.

Plate 5.2 FBC model structure (Cuttle (2011) personal communication)

The green boxes contain basic data used to run the simulations. These are the ones eligible for enhancement, in the investigation described in section 5.4. The yellow boxes contain the monthly time-step calculations for the entire arable rotation feeding into the profile and summary boxes and ultimately the printout. Plate 5.3 is example of an FBC model output summary.

Plate 5.3 Example of FBC model output

(Cuttle, 2006)

5.4 FBCmodel simulations – methodology

It was decided to test the model in its standard format against the results obtained from the FBC Coates Manor Farm FBC field trial reported in chapter 4 and root data obtained from the pot experiment described in chapter 3. The background data input is detailed in 5.4.1 below. The results obtained from the following direct sown FBCs only were considered since these were the only options available within the model as presently constituted:
Vetch (*V. villosa*), peas (*P. sativum*.), white lupins (*L. albus*.), red clover (*Trifolium patense* L.) ("cover crop") and natural regeneration fallow ("weeds").

The field trial results from the selected FBCs were then compared with the following model predictions (see 5.4.2):

FBCs: Biomass yields, N content in straw, roots, and whole plants.

Soil: SMN (SMN figures were compared rather than PMN because of the impossibility of calculating "standard" PMN figures for the model).

Test crop (winter wheat, *T. aestivum* L.): Biomass yields and grain yields

Having reviewed the results of the initial simulations (5.4.3) some proposals were made for enhancement of the model using the site-specific data from the field trial, and these were again tested against the full field trial results and evaluated using covariance and correlation analysis (5.4.4 and appendices 3.3)

5.4.1 FBC model data inputs

The Coates Manor Farm field trial site (West Field) location and history were entered into the model to provide the basis for the initial simulation. Intially the model was set to run in standard format, so as to be able to assess how well the parameterisation reflected the actual experimental site and FBCs. The data inputs are described below.

Table 5.2 Basic site and ley description.

Input	Field trial background data inputs
Description of site and soil type	
UK region	South West Engalnd and South Wales
Annual rainfall	800 mm (20 year average 801)
Dominant soil type	Shallow
Description of the ley	
Type of ley	White clover / grass ley
Age of ley	1 year
Proportion of legume	Low legume
Management	Cut and removed
Number of cuts per year	2 cuts
Manure applied to the ley	None
Previous cropping	Long term arable
Date of incorporation of the ley	August 28th

The soil series (Sherborne series Cotswold Brash (Findlay *et al.,* 1984) at the experimental site was thought to be best described by the “shallow” category. The experimental site was a long term arable site, however the FBC model requires a “ley” phase to set the initial parameters for the arable phase.

Therefore a low legume content, 1 year white clover (*T. repens*) and grass ley was felt to be best suited to the experimental site cropping history with the FBC crops to be modelled in sowing year 3 (see table 5.3).

Table 5.3 Arable cropping phase data inputs.

Input		Experiment data inputs				
		Sowing year 1	**Sowing year 2**	**Sowing year 3**	**Sowing year 4**	**Sowing year 5**
Description of arable crops		2005	2006	2007	2008	
Crop 1	Crop name	Winter Barley	Stubble Turnips (Grazed)	Fertilty building crop	Winter Wheat	
	Sowing date	23rd Sept	17th Aug	27th April	26th Sept	
	Harvest date	4th Aug	18th Dec	17th Aug	26th Aug	
	Proportion of weeds in the crop			See FBC table		
	Straw / residue removed at harvest?	N	N	N	N	
Crop 2	Crop name			Winter Wheat		
	Sowing date			26th Sept		
	Harvest date			26th Aug		
	Proportion of weeds in the crop					
	Straw / residue removed at harvest?			N		
Description of manure applications						
	Type of manure	No applications	No applications	No applications	No applications	
	Application rate					
	Application date					
	Delay to incorporation					

The cropping history was taken from the RAC farm records. The FBCs were inserted in year 3 to give the model the best opportunity accurately to simulate the trial site history. Previous cropping regime was taken from the experimental site, however no data on yield levels or weed levels (very low) were available. The FBCs selected were those for which parameters had already been written into the FBC model Cuttle [personal communication]. Red clover was parameterised as a "cover crop".

Table 5.4 Arable cropping FBCs data inputs

Input	**Trial FBC data inputs**				
Description of arable crops					
Crop name	Lupins	Peas	Vetch	Red Clover ("Cover crop")	Natural regeneration fallow ("Weeds")
Sowing date	27th April	27th April	27th April	27th April	27th April
Harvest date (crops mulched and interred)	17th Aug	17th Aug	17th Aug	17th Aug	17th Aug
Proportion of weeds in the crop	Low	High	Low	Medium	100%
Straw / residue removed at harvest?	N	N	N	N	N

5.4.2 Initial simulations

Table 5.5 Initial FBC model DM yield predictions and trial results

FBC Biomass yield (t DM ha^{-1})		
FBC	**Trial**	**Model**
Vetch	3.12	6.3
Peas	7.66	6
Lupins	6.86	4.4
Cover crop/ Red Clover	1.53	2.9
Weeds/ Fallow	3.23	1.5
Standard error of trial means	**0.507**	

FBC model yield predictions were quite different to those obtained in the field trial, the disparity ranging from 1.37t ha^{-1} (red clover) to 3.18t ha^{-1} (vetch). The field trial vetch FBC was a well-established and apparently good yielding crop. The yield predicted was probably more comparable with southern European yield levels than the UK. European examples are featured in the FAO – Grassland Species website (Frame, 2005) where Moreira (1989) observed yields of 5.81- 6.56 t ha^{-1} in northern Portugal and in central Spain figures of 6.51 t ha^{-1} were reported by Haj Ayed *et al*. (1995). Koivisto (2002), also working on Coates Manor Farm, obtained similar yields of forage peas to those in table 5.5. However, the yields of white lupin obtained by Azo (2007) (on a site with a more suitable soil pH) far exceeded those obtained in the current trial. The yield of red clover appears low however this was the DM accumulated during a relatively short period from the 27th April to the 17th August.

Model DM yields are determined by N supply and all other factors such as soil pH, other nutrients, soil conditions are not limiting growth, in addition the model does not take into account the effects of pest / disease occurrences.

Table 5.6 Initial model predictions of FBC N content compared with trial results

FBC N content (kg N ha^{-1}) in biomass						
FBCs	Trial	Model	Trial*	Model	Trial	Model
	Above-ground	Straw (+grain)	Roots*	Roots	Whole plant**	Whole plant (+ grain)
Vetch	122.73	175	7.92	43.6	130.82	218.6
Peas	241.22	46 (267)	2.16	42.9	255.88	88.9 (267)
Lupins	194.3	24.9 (126)	19.45	51	224.57	75.9 (126)
Cover crop / Red Clover	72.61	55.2	26.82	12.9	99.1	68.1
Weeds/ Fallow	66.6	30	7.93	9	65.09	39
Standard error of trial means	16.52		1.641		20.16	

*Root data is extrapolated from the pot experiment.
** Whole plant data is taken from the field (above-ground) and pot experiment (below-ground).
() Bracketed figures are the levels of N the model predicts are removed including grain

As previously described the model separates the crops into top crop (grain), straw (residues/ stubble) and roots, and as a result the trial results are not comparable with the model unless the grain is added to the straw figure. The model has provision to allow management decisions such as straw incorporation but does not allow any whole crop to be interred for fertility building. The difference between predicted and actual N content in above-ground biomass ranged from a 17.41Kg N ha^{-1} for red clover to a substantial difference of 71.78 Kg N ha^{-1} for peas. The root figures obtained from the pot experiment (chapter 3), apart from red clover, were substantially lower than the predictions, and subsequently impacted on the whole plant figures. This may, however, be due to the nature of the pot experiment to some extent restricting root development.

Table 5.7 Initial model predictions of winter wheat test crop yields in 2007 compared with trial results (grain on DM basis)

Winter Wheat yield (t ha^{-1})				
FBCs	**Trial Biomass**	**Model Biomass**	**Trial Grain**	**Model Grain**
Vetch	4.3	6.9	3.1	4.4
Peas	4.3	5.3	3.2	3.4
Lupins	4.3	5.3	3.3	3.4
Cover crop/ Red Clover	4.7	5.4	3.7	3.4
Weeds / Fallow	4.1	5.4	2.9	3.4
Standard error of trial means	0.392		0.228	

The predictions for winter wheat biomass yield were higher than the actual figures achieved in the trial. The grain yields were on average slightly below the model predictions, and well below the average UK organic growers of 4.7t/ha (Taylor *et al.,* 2001). Furthermore, excessive rainfall during the harvest period of 2007 delayed combining until the 26th August 2008, and some yield could certainly have been lost as a result. Vetch whole plant N levels were higher in the model prediction (table 5.6) than in the field trial, and this could account for the high grain yield prediction following vetch. Red clover is described within the model as a cover crop, which covers a broad spectrum of potential crops. However, the predicted whole plant N content did not reflect the levels achieved by the red clover treatment in the field trial.

Table 5.8 Initial SMN model predictions for the post FBC incorporation period.

Months post FBC incorporation	SMN levels (kg N ha^{-1})									
	Vetch		Peas		Lupins		Red Clover		Fallow	
	Trial	Model	Trial	Model	Trial	Model	Trial	Model	Trial	Model
November	9.94	52.6	12.26	8	8.66	12.3	19.4	21.1	10.03	37
December	9.39	47.4	7.74	7.1	7.09	9.8	10.09	15.9	11.24	25.9
January	6.9	39.2	6.63	10.7	7.01	12.1	10.07	16	7.59	21.9
February	9.49	34.6	6.58	13.5	9.14	14.2	10.31	16.6	9.86	20
March	5.06	13.4	3.4	0	4.99	0	6.02	0	3.78	0
April	4.38	0	3.6	0	4.63	0	6.45	0	3.45	0
May	7.91	0	7.74	0	8.87	0	8.06	0	5.98	0
June	3.76	0	5.31	0	6.25	0	6	0	4.6	0
July	8.72	1	6.14	0	6.81	0	10.34	0	10.1	0
August	9.3	22.5	11.5	16.6	11.8	15.8	21.7	15.7	24.2	13.8
Correlation coefficient - R	**0.62**		**0.63**		**0.70**		**0.71**		**0.19**	
Linear Regression	**y=5.7x - 21.5**		**y = 1.39x - 4.25**		**y = 2.27x - 10.66**		**y = 1.19x - 4.40**		**y = 0.86x + 4.03**	
Regression coefficient - R^2	**0.39**		**0.40**		**0.49**		**0.51**		**0.14**	
Regression significance	**NS**		**P< 0.05**		**P< 0.05**		**P< 0.05**		**NS**	
Repeated measures ANOVA (P value)	**<0.001**		**0.002**		**0.016**		**0.009**		**0.035**	

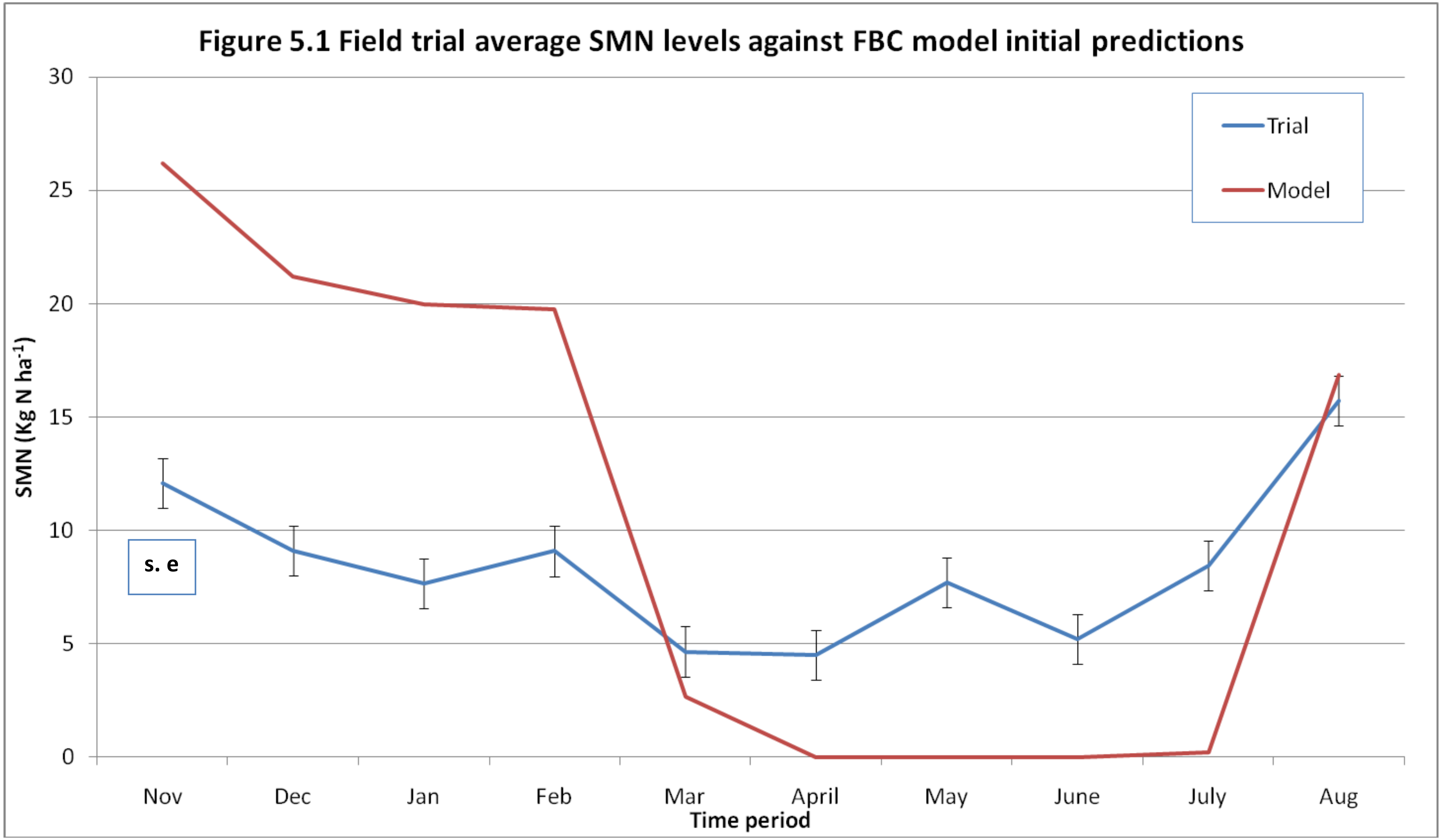


Figure 5.1 Field trial average SMN levels against FBC model initial predictions
30
25
20
15
10
5
0
SMN (Kg N ha-1)
Trial
Model
s. e
Nov
Dec
Jan
Feb
Mar
April
May
June
July
Aug
Time period

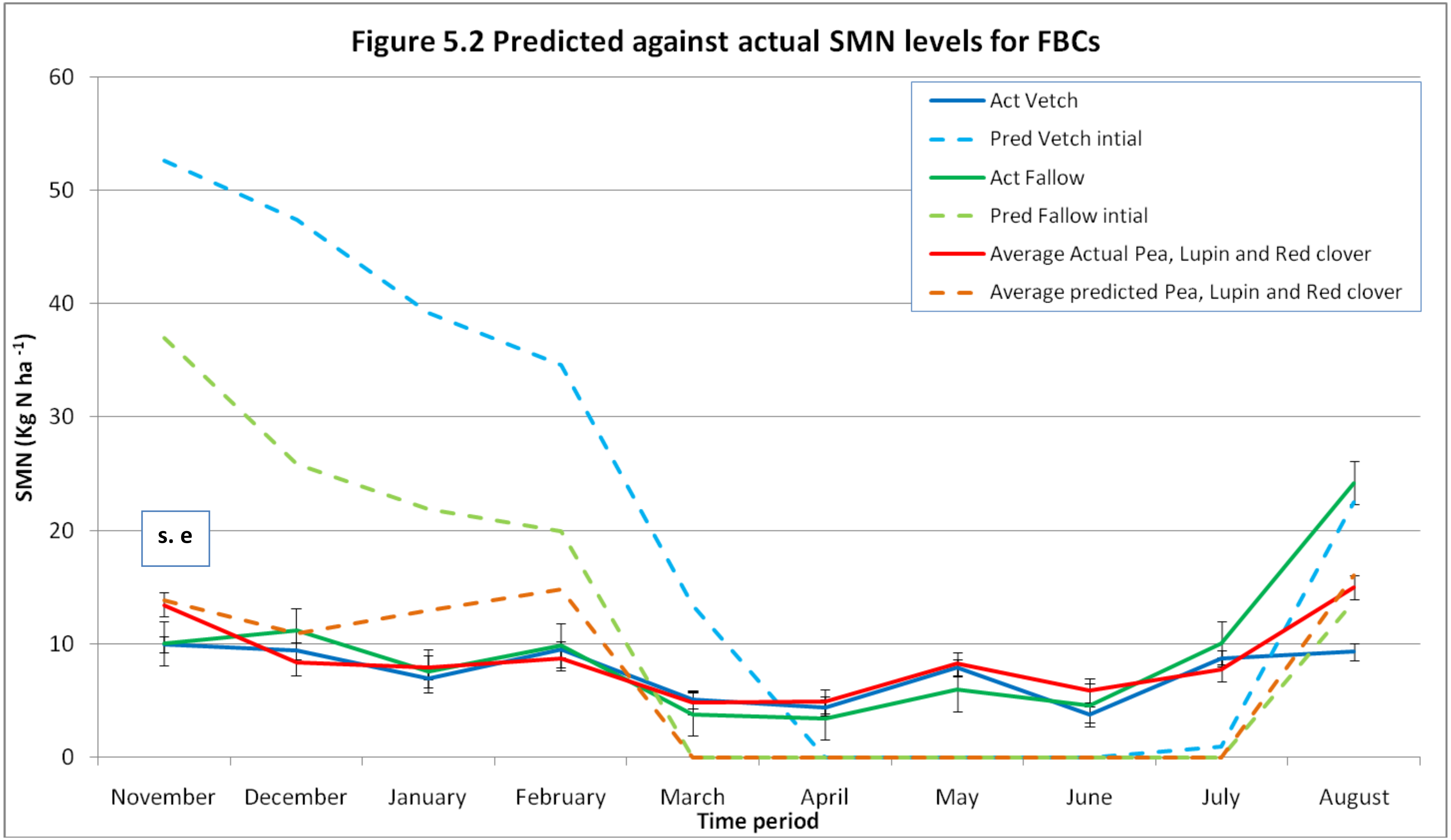


Figure 5.2 Predicted against actual SMN levels for FBCs
SMN (Kg N ha -1)
60
50
40
30
20
10
0
s. e
November
December
January
February
March
April
May
June
July
August
Time period
Act Vetch
Pred Vetch intial
Act Fallow
Pred Fallow intial
Average Actual Pea, Lupin and Red clover
Average predicted Pea, Lupin and Red clover

5.4.3 Review of initial simulations

The FBC predictions were substantially different from the actual figures obtained in the field trial, and the biomass yields predicted were up to 3.18 t ha^{-1} adrift. As a consequence of the biomass figures being a poor reflection of this experiment the prediction of N levels assimilated also differed substantially from the evaluated trial. The model predictions of winter wheat grain yields as a consequence of FBC incorporation were reasonable for the grain legumes but very high for vetch. SMN levels appeared to be strongly correlated with the actual figures obtained for the grain legumes, vetch and “cover crop” red clover (Table 5.8). Fallow showed a much poorer correlation with the model. The FBC model predicted a much greater N mineralisation from vetch than was actually observed during the period November to March (Figure 5.2). Overall the model showed only a “medium” correlation (R= 0.35) (Choudhury, 2009) with the actual SMN figures obtained from the field trial. The model predicts SMN values falling to zero during the months of April to July; this is unlikely to happen in practice because not all the SMN will be available to roots.

5.5 FBC model enhancements

Having identified the shortcomings of the model, the logical parameters for modification based on the site and season specific information that the trial could offer to create a series of enhancements, are as set out in tables 5.9 - 5.11.

Table 5.9 Above-ground FBC parameters

Selected FBCs	Parameter	Model		Trial	
		Top crop	Straw / residues	Top crop	Straw / residues
	FW* yield t ha $^{-1}$				
Peas		5.4	5.4	14.565	14.565
White Lupin		3.2	4.24	14.856	19.69
Vetch			28.75		15.37
Red Clover			22.00		8.76
Fallow			5		12.71
	% DM of residues				
Peas			85		26.295
White Lupin			83		19.85
Vetch			22.6		20.29
Red Clover			20		17.465
Fallow			30		25.41
	% N of residues				
Peas		5.76	1		2.456
White Lupin		3.95	1.4		2.975
Vetch			2.8		3.489
Red Clover			1.9		3.454
Fallow			2.0		1.85
	% C of residues				
Peas			45		44.84
White Lupin			40		43.74
Vetch			45		43.38
Red Clover			40		43.36
Fallow			40		41.16

Table 5.10 Below-ground FBC parameters

Selected FBCs	Parameter	Model Root mass	Trial Root mass
	DM yield	t ha^{-1}	
Peas		2	0.091
White Lupin		2.4	0.705
Vetch		1.5	0.279
Red Clover		1.3	0.875
Fallow		0.6	0.284
	% N		
Peas		3	1.817
White Lupin		3	1.099
Vetch		3	1.754
Red Clover		1.5	2.145
Fallow		1.5	1.106
	% C		
Peas		45	35.212
White Lupin		40	35.895
Vetch		45	33.889
Red Clover		40	36.114
Fallow		40	34.025

Trial results are based on the pot experiment and field populations.

Table 5.11 Soil parameters

Soil	Parameter	Model	Trial*
Shallow	Clay <2mm	19	38
	% Organic C	1.46	6.93
	Total % N	0.15	0.438
	C:N ratio	10.0	15.4
	Million kg Topsoil ha^{-1}	2.89	2.75

* Site soil analysis – appendix 2.3

It was also considered appropriate to remove the vetch data from the enhanced model simulations because of the obvious over-prediction of N mineralisation during the autumn and winter months. In further enhancement vetch should be regarded as the crop with the greatest potential for improvement of data. In view of the likely effects on N mineralisation and leaching during the 2006/2007, cropping season it was also decided to substitute actual rainfall data from the RAC weather station at Cirencester (about 2 miles away) for the standard data included in the initial model simulations.

5.5.1 Results of the model enhancement exercise

A total of 38 options for model enhancement were considered. Since the objective of the investigation was to improve the predictability of the assessment of the residual fertility associated with specific FBCs it was also decided to concentrate this part of the investigation on the predictions of the SMN levels since such information is widely available in the agricultural industry following soil analysis, however it should be remembered that SMN levels are less reliable where large quantities of organic material have been added to the soil.

The results of the covariance and correlation analysis comparing the results from the field trial with the range of model enhancements are summarised below in tables 5.12-5.14 and figure 5.3 and 5.4, the entire data set is given in appendices 3.3.

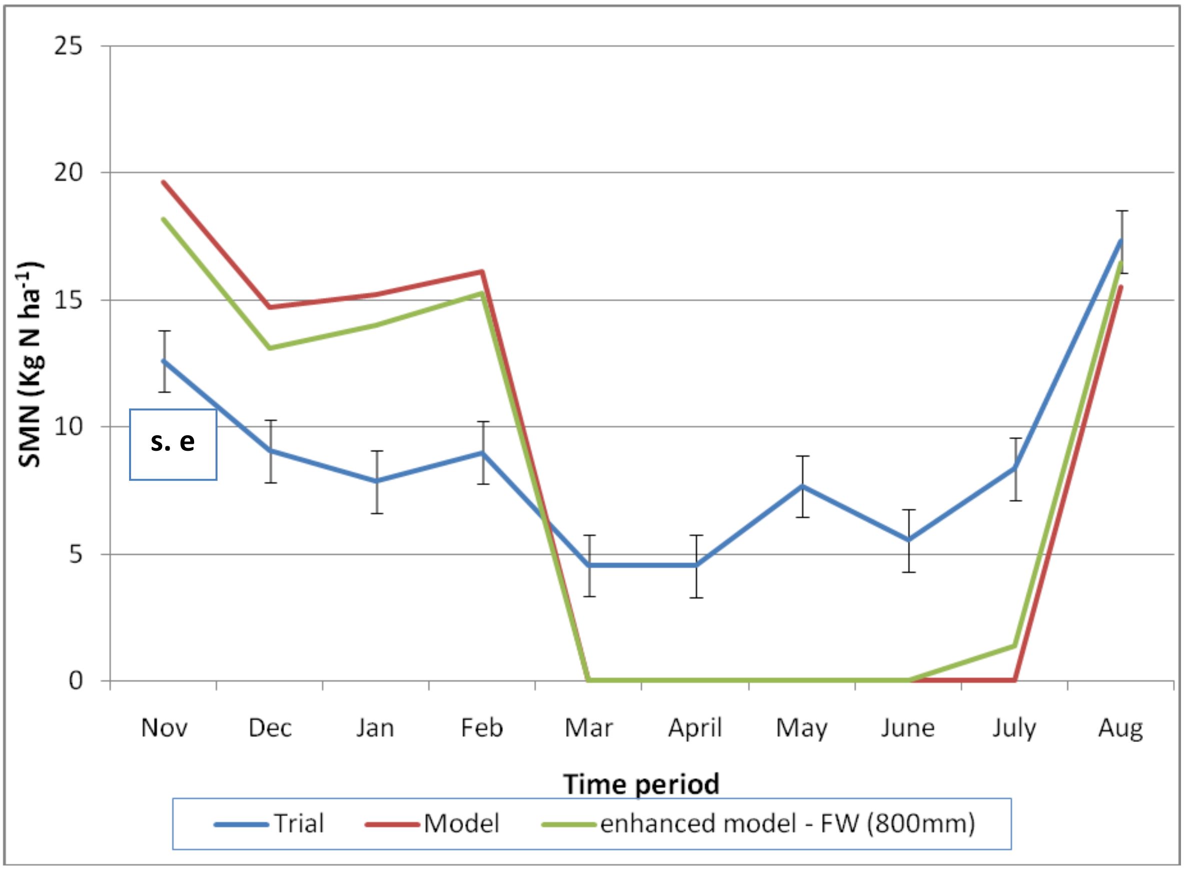
5.5.1.1 Results of residue enhancements

Table 5.12 Residue enhancements – correlation coefficients R for actual against predicted SMN November - August

Brief description of model enhancement	**Initial run 800mm rainfall**	**Without vetch 800mm rainfall**	**Without vetch 950mm rainfall**
Initial run	0.354	0.512	0.568
Initial + actual crop weed data (referred hereafter as Standard)	0.367	0.515	0.568
Actual FQs used	0.439	0.606	0.649
Actual FW above-ground + actual DM %	0.416	0.481	0.557
Actual % N in above-ground residues	0.262	0.456	0.526
Actual FW + actual % N above-ground	0.310	0.346	0.423
Actual FW + actual DM % + actual % N	0.311	0.339	0.419
Actual % N in roots	0.394	0.536	0.594
Actual FW + Actual % N in roots	0.450	0.605	0.602
Actual FW + actual % N (above and below-ground)	0.329	0.363	0.443
Actual FW + actual % N (above and below-ground) + actual DM % (above-ground)	0.346	0.390	0.457
Actual above and below-ground C:N ratios	0.297	0.346	0.570
Actual C:N ratios + actual FW	0.161	0.170	0.450
Actual C:N ratios + actual FW + actual root DM yield	0.219	0.214	0.448
Actual C:N ratios + actual FW + actual DM % + actual root DM yield	0.379	0.413	0.453

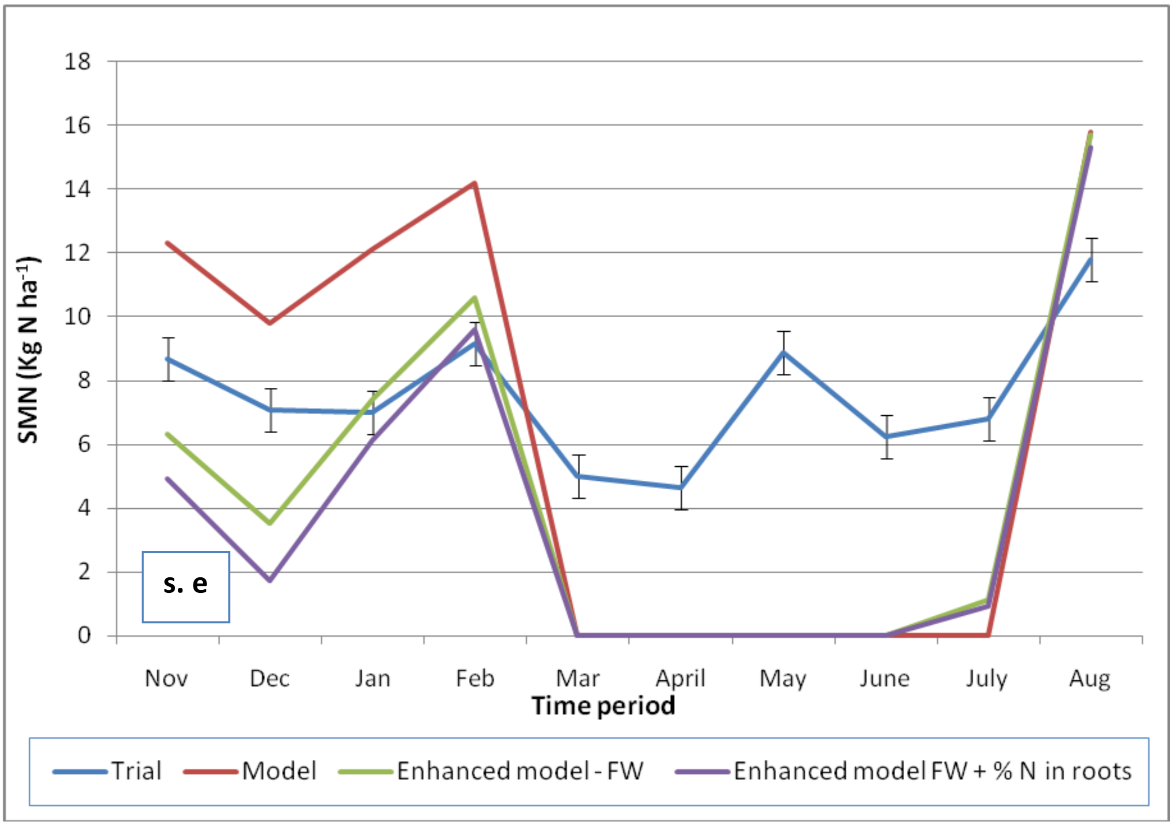
Modifications to the FBC FW and in combination with % N in root material provided the most significant improvements over the initial prediction and the best correlations with the actual field trial data. Simple additions of accurate FW data demonstrated the strongest correlation (R 0.606) of the model with the actual SMN levels measured. Accurate data on N % within FBC roots obtained from the pot experiment also demonstrated a good correlation (R 0.536), the combination with FW data (R 0.605; Figure 5.3) confirmed that these parameters are key to successful predictions. The relationship with all FBCs (minus vetch), and the individual analyses of FBCs are shown in appendix 3.3.7; 3.3.10; 3.3.11; 3.3.12 and 3.3.13.

Figure 5.3 Soil Mineral N (Kg N ha $^{-1}$) trial averages against predictions (model enhancement – actual FW, 800mm rainfall)



It should be remembered that SMN is the differences between N release and N uptake and discrepancies in the model estimates could be due to errors in either the mineralisation or uptake estimates. Individual FBC analysis indicated that no further improvements could be made to the Fallow predictions irrespective of the modifications. This is likely to have been due to the diverse nature of the species present. Individual analysis also indicated that lupins (type not specified in the model) had the strongest correlations of the FBCs with FW yield alterations (R = 0.783). Figure 5.4 demonstrates the strong correlation (R = 0.792) between actual and predictions with model modification to the actual trial FW and % N in roots.

Figure 5.4 Lupins soil mineral N (Kg N ha^{-1}) trial averages against model predictions



The optimal parameter for pea predictions was the modifications of FW yield (Statistical Coloration (R) = 0.699) which represented a situation where the entire crop was interred into the soil. As previously indicated, enhancement of the fallow data resulted in only small improvements to the already weak correlation. When the fallow data was removed from the SMN prediction (appendix 3.3.8) there were substantial improvements in the predictions, for example FW and FW plus % N in roots enhancements improved R from 0.606, 0.605 to 0.701, 0.703 respectively.

5.5.1.2 Results of soil enhancements

Table 5.13 Soil enhancements – correlation coefficients R for actual against predicted SMN November – August.

Brief description of model enhancement – Soil properties	**R**
Standard	0.515
Standard + actual % clay	0.478
Standard + actual % SOC	0.478
Standard + actual % soil N	0.443
Standard + actual % soil C:N ratio	0.443
Standard + actual topsoil depth	0.476
Standard + actual % clay + actual % SOC	0.478
Standard + actual % clay + actual % soil N	0.443
Standard + actual % clay + actual % soil C:N ratio	0.478
Standard + actual % clay + actual topsoil depth	0.476
Standard + actual % SOC + actual topsoil depth	0.476
Standard + actual % SOC + actual % soil N	0.443
Standard + actual % soil N + actual topsoil depth	0.447
Standard + actual soil C:N ratio + actual topsoil depth	0.476
Standard + actual % clay + actual % SOC + actual % soil N	0.445
Standard + actual % clay + actual % SOC + actual % soil N + actual topsoil depth	0.443

The “shallow” soil series described within the model may not accurately fit the Sherborne soil series soil parameters (Table 5.11); however no modifications with soil specific data enhanced the relationship between actual and predicted SMN levels over the initial run levels.

5.5.1.3 *Results of Residue and soil enhancements*

Table 5.14 Combination of enhancements – correlation coefficients R for actual against predicted SMN November – August.

Brief description of model enhancement – Combination of Residue and Soil properties	R
Standard	0.515
Standard + actual FW + actual % soil N	0.447
Standard + actual FW + actual soil C:N ratio	0.447
Standard + actual FW + actual % soil N + actual topsoil depth	0.454
Standard + actual FW + actual soil C:N ratio + actual topsoil depth	0.454
Standard + actual FW + % N in roots + % soil N	0.456
Standard + actual FW + % N in roots + soil C:N ratio	0.449
Standard + actual FW + % N in roots + % soil N	0.456
Standard + actual FW + % N in roots + soil C:N ratio + actual topsoil depth	0.456

The combinations of properties were intended to identify the optimal model enhancements; however the addition of the soil properties to the residue characteristics actually reduces the strength of the correlation between residue properties and their influence on predictions for SMN levels post FBC incorporation.

5.5.1.4 *Results of model enhancements on FBCs whole plant N levels (Kg N ha^{-1})*

Table 5.15 Model enhancements on FBC whole plant N levels (kg N ha^{-1}) predictions

FBCs	Trial	Model initial	Enhanced model	
			FW	FW + % N in roots
Vetch	130.82	218.6	141.6	123.6
Pea	255.88	88.9 (267)	66.9 (239.7)	62.9 (316.34)
Lupin	224.57	75.9 (126)	46.4 (161)	37.4 (152)
Red clover	99.1	68.1	53	56.3
Fallow	65.09	39	55.2	55.2

The residue enhancements which most strongly influenced the predictions of whole plant N levels were accurate FW data and a combination of FW and % N in FBCs roots. The strengthening of the whole plant predictions influenced the correlation between actual and predicted SMN levels. Initial prediction overestimated vetch by 88kg N ha^{-1} and underestimated the other FBCs by 26-167 kg ha^{-1}. Following enhancements to the model, whole N content was best reflected by FW yields for peas and lupins, although lupin predictions were still 63.6kg ha^{-1} adrift, whilst vetch and red clover responded best to FW plus % N in roots.

5.5.1.5 Results of model enhancements on winter wheat grain yield

Table 5.16 Model enhancements on winter wheat grain yield (t ha^{-1})

FBCs	Trial	Model initial	Enhanced model	
			FW	FW + % N in roots
Vetch	3.1	4.4	4	3.9
Pea	3.2	3.4	3.4	3.2
Lupin	3.3	3.4	3.1	3.1
Red clover	3.7	3.4	3.4	3.4
Fallow	2.9	3.4	3.4	3.4

The ultimate test of a model is its capacity to predict the following crop grain yield, as this is the economic driver in a crop rotation and the final stage in the predictions from FBCs N content, through residue release in the soil (SMN) to crop uptake. The initial model run demonstrated good predictions for peas and lupins, and to a lesser extent red clover. Relatively poor predictions were demonstrated for vetch and fallow. The closest overall predictions for FBCs grain yield was demonstrated by FW plus % N in roots, the range between actual and predicted is 0 – 0.8t ha^{-1}, none of the enhancements influenced the fallow grain yield below 3.4 t ha^{-1}.

5.5.1.6 Model conclusions

The strongest correlations were obtained from modifications to the residue properties, in particular the use of FBCs' actual FW yields, the actual N percentage in roots and a combination of these factors. Soil properties described as "shallow" within the model appeared adequately to describe the Sherborne series soil in the West field trial site, although this is not necessary evidence that all of the model's soil factors are correct. The use of actual data had a negligible or negative effect on the correlation between actual and predicted SMN levels post FBC incorporation compared to the model initial run data set.

5.6 Discussion

Accurate FBC parameterisation is key to successful simulations. The strong correlation between legume FW yields and N fixation has been described by various authors (Hardarson and Atkins, 2003; Kumar and Goh, 2000), and extrapolated further to provide guidance on N accumulation levels (Cuttle and Goodlass, 2004; Tonitto *et al.,* 2006). The literature emphasises the importance of FW amelioration for optimal N accumulation (Fageria, 2007, Tonitto *et al.,* 2006) but also to mitigate pre-emptive competition (Thorup –Kristensen *et al*., 2003), plus soil physical, chemical and biological problems (Fageria, 2007). The enhancements of the FBC model to obtain stronger correlation with the current field trial data emphasised the importance of accurate simple parameters (FW yield and %N) in the assessment of FBC behaviour once incorporated. Accurate FBC information on FW yield data was critical to the model, and should be easily obtainable by farmers / advisers. Greater difficulties may be encountered when dealing with longer term leys. For example Berntsen *et al.,* (2006) described simple vegetation harvests of known areas to a cutting height of 2-3cm to obtain such data.

Soil moisture plays a critical role in crop growth and the activity of soil micro-flora and fauna (Blantern,1991; Broadbent, 1986), hence the intrinsic link between soil moisture content and mineralisation (Kumar and Goh, 2002). Optimum WHC is 60% for mineralisation, but high sustained levels of rainfall can induce higher leaching levels (Gill *et al.,* 1995). The field trial site over the test cropping phase (2006/2007) experienced rainfall 130mm in excess of the 20 year average for the area. As demonstrated in the results this had a substantial impact on the SMN level correlations between actual and predicted data. This indicates the importance of the use of accurate rainfall data for advisers in the predictions of FBC plant material behaviour after incorporation.

FBC root material is considered an important factor within the literature, with Watson *et al.,* (2002) and Jørgensen and Ledgard (1997) detailing the need to correct N accumulation figures for below stubble height data. The model enhancements emphasise the importance of accurate assessments of % N in the root mass but to a lesser extent than FW yield. However the combination of both factors produced the closest predictions to actual grain yields and with vetch and red clover, whole plant N accumulation. The actual pot experiment data for vetch, peas and lupins was between 1.1-1.8% lower in N concentration than the model predictions. Although root % N in combination with other factors demonstrated good correlations, root biomass was less successful. Root biomass estimates in the pot experiment were 0.3-1.9t DM ha^{-1} lower than those predicted by the model. Although Radha and Srinivasan (2008) suggested pot experiments were suitable for assessing biometric root parameters, a number of other authors (Bell *et al.,* 1997; Xavier *et al.,* 1993) have demonstrated that pot experiment results did not adequately replicate field trial results despite using the same soil. Recovery of root biomass, particularly fine root material can be difficult to obtain completely (Koné *et al.,* 2008).

The poor predictions of the residue mineralisation of vetch may have been attributable to the erroneous partitioning of incorporated material into residue pools. In the model vetch partitions 36% and 38% of above and below ground residues into the fast pool, which is the highest of all featured FBCs. As previously discussed this theoretical partitioning of residues is critical to successful simulations (Cuttle and Goodlass, 2004). High metabolic components found within FBCs have also caused partitioning inaccuracies within DAISY in the Muller *et al.,* (2003) and De Neergaard *et al.,* (2002) experiments. Future modifications of vetch portioning between pools in the FBC model should be modified to prevent over estimation of SMN levels post-residue incorporation.

Promsakha Na Sakonnakhon *et al.,* (2006) experiment demonstrated that differing weed populations resulted in significantly different DM and N accumulation figures, and behaviour once incorporated. The model enhancements did not produce strong correlations between predicted and actual SMN levels for the fallow treatment. This was probably a reflection of the diversity of weed population and composition which can vary according to cropping sequence (Ekeleme *et al.,* 2003), timing and management (Egley, 1986), the soil weed bank and soil fertility status (Promsakha Na Sakonnakhon *et al.,* 2006).

5.7 Conclusions and recommendations for further enhancement

- FW yield estimates should be as accurate as possible.

- Actual rainfall data for the site should always be used in preference to a standard figure.

- Model predictions of SMN levels (Table 5.8) for all FBCs from April to June were at zero indicating that the winter wheat test crop was removing all of the SMN from the profile. This is not a likely reflection of a field situation as crop roots are rarely able to deplete N levels to this extent. This area within the model would benefit from modifications more accurately to replicate field conditions.

- The fallow treatment attempted to encompass a wide range of species and their respective attributes. A refinement of this parameter into predominantly broadleaved, grass or combination may more accurately describe the overall populations and may aid predictions.

- The use of short term FBCs or “cover crops” as described in the model offer the opportunity for a “boost” in fertility without incurring pronounced opportunity costs. Crops which demonstrated beneficial results in the field experiment which currently are not represented in the model are red and white clovers and a mixture of legumes, which should be considered for future inclusion in the model.

Chapter 6 General Discussion

6.1 Potential FBC utilisation

The cost of nutrient supply in the form of inorganic N fertilisers are a limiting factor to the economic sustainability of agribusinesses. Grain prices have and will continue to fluctuate with world-wide weather or political events (FWI, 2012; Organisation for Economic Co-Operation and Development (OECD)/FAO, 2011). The critical economic return for the profitable utilisation of N fertiliser has eased over the period 2007 - 2011 due to improved wheat prices and slightly lower fertiliser costs and the breakeven ratio for the economic response of winter to fertiliser N has improved from 3:1 to 5:1 in the latest guidelines (DEFRA, 2010). The important role that N fertiliser plays in world food production has already been established (chapter 2). There has been some debate whether *Rhizobium* association with leguminous crops can supply sufficient N yield to sustain the current global population. This ranges from “entirely possible” (Goulding *et al.,* 2009) to “unfeasible” (Smil, 1999; Dawson and Hilton, 2011). Dawson and Hilton (2011) suggest that the Haber Bosch technique is likely to remain a reliable, effective method of supplying inorganic N. They also suggest, however, that further sustainability can be derived from the opportunist use of leguminous crops and other FBCs to moderate inorganic N usage and to improve the overall NUE of crop residues.

The use of short term FBCs also offers the opportunity to fulfil some of the recommendations by a recent report (Commission on Sustainable Agriculture and Climate Change, 2012), whereby sustainable intensification may be achieved by mechanisms such as diversified crop rotation, improvements to soil “health” and improved nutrient use efficiency. The Commission highlights that “farmers struggle to balance pressures for short-term income and the longer-term benefits associated with shifts to more sustainable practice”. It is this argument against the associated opportunity costs which is often used to rule out straight sown FBC fertility building phases (Tonitto *et al.,* 2006), which is further borne out by the results cited in chapter 4. However, this research together with that of Bergkvist *et al.,* (2011) has further identified and quantified the potential for fertility building using undersown FBCs, without incurring yield penalties and improving subsequent crop nutrition.

6.2 FBC Selection

All of the legume FBCs (white lupin, black medic, vetch, peas, crimson, sweet, red and white clovers) selected nodulated successfully (some with inoculant) and demonstrated signs of atmospheric N fixation. This confirms these leguminous crops as being suitable for inclusion as N fixation crops within UK soil / climatic conditions. An outcome of this investigation is a better knowledge of selected FBC morphology, N accumulation and residue quality. The marked differences between above-ground and below-ground characteristics provided an important insight into N accumulation. This also informed understanding of the residue behaviour within the field trial and may act as a useful benchmark for future investigations. Percentage N in FBC roots was also an important parameter for accurate modelling of N mineralisation in the FBC model (Cuttle *et al,* 2003, chapter 5); this will be useful for future verification and / or the addition of new FBC data within the model. Root mass, especially the recovery of fine root material was difficult in the pot experiment. Comparison with root mass in the field trial would have been desirable, but was unachievable due to the high stone content and the destruction of the plots which would have modified future soil profile results.

Table 6.1 Summary of FBC properties

FBCs	Sowing regime	Weed suppression capacity	DM yield	Whole plant (Aug 2007) %N	Whole plant (Aug 2007) C:N	Impact on N status (PMN)	Extra yield of test crops $t\ ha^{-1}$ ◊ over control	Other properties
Benchmark control for comparing FBCs and establishment methods performance is non-undersown Spring Barley (“undersown fallow” in the treatments described in chapter 4).							**WW Control 2.13 $t\ ha^{-1}$ ^{a}** **SW Control 1.94 $t\ ha^{-1}$ ^{a}**	All subsequent yield figures cited in this table are the increases over the control figures. Significant differences ($P<0.05$) are identified between the control figures and FBCs for each of the test crops and establishment regimes using superscript letters.
Fallow	**Natural regeneration (“Straight sown”)**		Moderate	<2.0	>20	Low	WW + 1.29 ^{b} SW + 1.10 ^{bcd}	• Cheap, very variable in composition and yield; can act as temporary nutrient storage if weeds are destroyed prior to seeding • May perpetuate problem weeds • Increases biodiversity
White Lupin	**Straight sown**	Very Good	High	2-3	15-20	High	WW + 1.74 ^{bcd} SW + 0.94 ^{abc}	• Dominates spring barley cover crop, which may cause harvesting difficulties • Only suitable as a sole grain crop or as a bi-crop for wholecrop forage • Sensitive to soil pH
	Undersown	Excellent	High			Moderate	WW + 0.04 ^{NS} SW + 0.61 ^{ab}	
Crimson Clover	**Straight sown**	Good	Low	2-3	15-20	Moderate	WW + 1.43 ^{bc} SW + 0.84 ^{ab}	• Low percentage ground cover (few lateral branches) • A high risk of winter kill in the UK in exposed sites (as overwintered in the pot exp.)
	Undersown	Comparable with fallow	Moderate			Moderate	WW + 0.4 ^{NS} SW + 0.23 ^{a}	

FBCs	Sowing regime	Weed suppression capacity	Yield	Whole plant (Aug 2007)		Impact on N status (PMN)	Extra grain yield t ha^{-1} ◊ over control	Other properties
				%N	C:N			
Black Medic	**Straight sown**	Good	Low	2-3	15-20	High	WW +1.73 ^{bcd} SW + 1.35^{bcd}	• Low prostrate crop, capable of being undersown without hindering spring barley harvest. • Successfully overwintered, with the highest spring biomass levels.
	Undersown	Comparable with fallow	Low			Moderate	WW + 0.49 ^{NS} SW + 1.55 ^{c}	
Vetch	**Straight sown**	Very Good	Moderate	>3	<15	Very High	WW +1.49 ^{bc} SW + 0.86 ^{ab}	• Scrambling effect can cause lodging of spring barley • Suitable for wholecrop forage or grazing • Overwintered poorly in the field trial, but demonstrated some level of regeneration in the pot experiment.
	Undersown	Comparable with fallow	High			Moderate	WW + 0.26 ^{NS} SW + 0.94 ^{bc}	
Sweet Clover	**Straight sown**	Very Good	Moderate - High	>3	<15	Low	WW + 1.52 ^{bc} SW + 1.51 ^{bcd}	• Dominates spring barley cover crop, which may cause harvesting difficulties. • Can cause scenting problems in malting barley rotations (Warminster Maltings, Pers Comm). • Biennial crop which successfully regenerated in the pot experiment, but not in the field trial.
	Undersown	Comparable with fallow	Moderate			Low	WW + 0.32 ^{NS} SW + 0.48 ^{ab}	

FBCs	Sowing regime	Weed suppression capacity	Yield	Whole plant (Aug 2007)		Impact on N status (PMN)	Extra grain yield t ha^{-1} ◊ over control	Other properties
				%N	C:N			
Red Clover	Straight sown	Good	Low	>3	<15	Very High	WW + 2.25 ^{de}	• Poor levels of regeneration in the spring prior to incorporation yet regenerated well in the more sheltered pot experiment. • Undersowing is possible, but it may cause more harvesting difficulties for cover crops than more prostrate species.
							SW + 1.90 ^{d}	
	Undersown	Comparable with fallow	Moderate			Moderate	WW + 0.89 ^{NS}	
							SW + 1.03 ^{bc}	
White Clover	Straight sown	Good	Low	>3	<15	High	WW + 2.42 ^{e}	• Low prostrate crop, capable of being undersown without hindering cover crop harvest. • Successfully overwintered in the field trial.
							SW + 1.11 ^{bcd}	
	Undersown	Comparable with fallow	Low			Moderate	WW + 0.67 ^{NS}	
							SW + 1.05 ^{bc}	
Mixture	Straight sown	Good	Moderate	>3	<15	Moderate	WW + 2.07 ^{cde}	• Successfully overwintered in the field trial with the exception of sweet clover • Spreads the agronomic risk of crop failure.
							SW + 1.86 ^{cd}	
	Undersown	Comparable with fallow	Moderate			High	WW + 0.19 ^{NS}	
							SW + 1.36 ^{c}	

FBCs	Sowing regime	Weed suppression capacity	Yield	Whole plant (Aug 2007)		Impact on N status (PMN)	Extra grain yield t ha^{-1} ◊ over control	Other properties
				%N	C:N			
Phacelia	**Straight sown**	Excellent	Moderate – High	<2	>20	Very High	WW + 1.51 ^{bc} SW + 0.81 ^{ab}	• Overwintered material was regenerated from dispersed seeds. • Environmentally attractive, as a pollinator source. • Superior N lifter
	Undersown	Comparable with fallow	Low			Moderate	WW + 0.16 ^{NS} SW + 0.53 ^{ab}	
Peas	**Straight sown**	Poor	High	2-3	15-20	Low	WW + 1.67 ^{bcd} SW + 1.51 ^{bcd}	• Dominates spring barley cover crop with a scrambling growth habit which may cause harvesting difficulties • Only suitable as a sole grain crop or as a bi-crop for wholecrop forage
	Undersown	Excellent	High			Low	WW + 0.1 ^{NS} SW + 0.43 ^{ab}	

◊ - Yield levels over the non-undersown spring barley ("undersown fallow") control.
WW – winter wheat
SW – spring wheat
Significance level is P<0.05, FBCs with ^{NS} are not significantly different. Extra yields followed by the same letters for the same test crops are not significantly different.
The criteria for classifying weed suppression, yield and PMN levels are based on the significant differences between FBCs

- weed suppression (figure 4.2)
    - Straight sown (t DM ha^{-1}) Excellent - >0.25 Very Good – 0.26-0.75 Good – 0.76 – 1.3 Poor – < 1.31
    - Undersown – Comparable with fallow – no significant weed level difference over the fallow
        - Excellent - significantly superior weed suppression over the fallow.
- yield (figure 4.5 and 4.7)
    - Straight sown (t DM ha^{-1}) Low - >1.5 Moderate – 1.6 - 3 Moderate – High – 3.1 - 5 High – <5.1
    - Under sown (t DM ha^{-1}) Low - >0.5 Moderate – 0.6 – 1.5 Moderate – High – 1.6 – 2.4 High – <2.5
- PMN assessments (figure 4.12; 4.13 and table 4.5)
    - Straight sown (kg N ha^{-1}) Low - > 85 Moderate – 86-95 High – 96-110 Very High – <111
    - Under sown (kg N ha^{-1}) Low - > 88 Moderate – 89-95 High – < 96

Annual grain FBCs achieved the greatest levels of biomass production and weed suppression, consistent with Angus *et al.,* (2000). Low weed levels in undersown crops can be attributed to the cultural harrowing technique prior to FBC establishment, which removed many weed cotyledons (Brandsæter *et al.,* 2012; Eyre *et al.,* 2011). This technique has the potential to reduce crops weed burden, reduce herbicide usage which maybe environmentally and economically advantageous (Gilbert *et al.,* 2009; Kurstjens, 2007; Mouazen *et al.,* 2007; Løes *et al.,* 2011).

Perennial FBCs, red clover, white clover and the mixture most significantly affected test crop performance, with elevated biomass and grain yields. This can probably be attributed to a combination of high %N levels and low C:N ratios in residues. Further calculation of the uptake of the assimilation of N into winter biomass at harvest indicated the highest levels following the use of these FBCs. A mixture of legumes, encouraged higher N accumulation levels in biomass than its constituent components, except straight sown sweet clover. This may have been attributable to more aggressive nodulation as Bergtold *et al.,* (2005) suggests, or perhaps intra-legume competition induced higher N accumulation (The Organic Research Centre, 2011). A mixture with a combination of high %N and low C:N ratio in residues is agronomically attractive due to a reduction in the risk of crop failure and economically due to the fertilising effect on the subsequent crop. Legume LINK (The Organic Research Centre, 2011) also identifies mixtures as providing better weed control throughout the season and as being important resources for pollinators and the invertebrate community.

Cherr *et al.,* (2006) suggested the most suitable temperate botanical families for legume FBC selection were *Trifolium*, *Vicia*, *Medicago*, and *Lupinus*. This research covered all of these families within its selections, however Lucerne (*M. sativa)* has been widely featured in UK recommended FBCs (Henry Doubleday Research Association (HDRA), 2009; Cuttle *et al.,* 2003) and should probably have been considered for inclusion (although its characteristics are similar to sweet clover). The inclusion of another N lifter such as mustard (*S. alba*) or rye (*S. cereale*) may have been desirable as they have superior overwintering properties compared to *Phacelia*

(HDRA, 2009) and are suitable for temperate agricultural conditions (Cøerr *et al.,* 2006).
Straight sowing of FBCs for a 6 month period produced the greatest yield improvements in the winter wheat test crop; yield improvement was 1.29-2.42 t grain ha^{-1} equivalent to about £205-385 ha^{-1} (FWI March 2012 feed wheat grain price £159t) over the "control" (non-undersown spring barley). Undersowing did not incur the opportunity costs associated with straight sowing as there was no significant impact on the yield of spring barley. Undersown FBCs suppressed weed levels thereby enabling a possible reduction in herbicide use, as well as the increasing soil fertility resulting in a more environmentally and economically sustainable cropping system (LegumeLINK, 2011). However, weed mass in the spring barley crops undersown with FBCs apart from peas and white lupin were not significantly different.

Spring wheat performance was optimised by those perennial FBC treatments which overwintered successfully. Spring wheat satisfies the need for diversified rotations with lower variable costs in terms of inorganic nutrient and agro-chemical inputs. Within the straight sown treatments the mixture gave the maximum grain yield improvement at 1.86t ha^{-1}. However, more interestingly, a spring barley crop undersown with black medic produced a 1.55t ha^{-1} premium in the subsequent spring wheat crop with no yield penalty in the barley cover crop. This result resembles that obtained Bergkvist *et al., (*2011) who found an approximate 2t ha^{-1} yield premium in spring barley crop following winter wheat undersown with red or white clovers. The challenge as Cherr *et al.,* (2006) summarise is to re-integrate FBC techniques into the portfolio of agronomic options that conventional farmers / advisers use.

6.3 Nitrogen measurement and recommendation

Nitrogen monitoring within the soil is an important agronomic / economic tool for environmental and economic sustainability. SMN provides a snapshot of what is currently available, whereas PMN is a predictive tool which can be used to inform the planning of future fertiliser applications. Either of these techniques used in isolation could cause confusion, however, together they could provide a more informed picture from which to make more meaningful recommendations.

6.3.1 Fertiliser recommendations for West Field derived using RB209 guidance.

The basis of the RB209 system was described in chapter 2 section 2.4.2. Here, the Field Assessment (Table 6.2) and Measurement Methods (Table 6.3) have been applied to generate appropriate optimum N recommendations for the winter and spring wheat test crops in West Field using the data obtained from the field trial described in chapter 4.

Table 6.2 N Recommendations using the Field Assessment Method

Criteria for assessment	***Recommendation for winter wheat - West Field***	***Recommendation for Spring wheat – West Field***
Soil type	*Shallow*	*Shallow*
Previous cropping	*Beans, Peas*	*Beans, Peas*
Rainfall	*High >700mm*	*High >700mm*
Provisional SNS	***1***	***1***
Adjustments	*None*	*None*
SNS Index	***1***	***1***
Fertiliser recommendation (Kg N ha^{-1})	***240***	***180***

There being no provision for short term fertility building or for whole crop interment, the "peas and beans main crop" option was thought to give the best fit for comparison with treatments within the experiment. Adjustments recommended to the provisional SNS made on the basis of "previous leys in excess of 1 year" were not thought to be applicable for the fertility building phase in this research.

In table 6.3 recommendation one was calculated on the basis of the SOM technique recommended in RB209. RB209 also enables recommendations to be made with the use of data from an anaerobic incubation i.e. PMN (Lober and Reeder, 1993); it is suggested that this should be added to the other N figures. This calculation was made for winter wheat following non-undersown spring barley in Table 6.3 (recommendation 2 effectively a “do nothing” control) and for winter wheat following the direct sown peas (recommendation 4) and *Phacelia* (recommendation 5). Recommendation 3 was calculated using the averages of all the direct sown FBCs. No use was made of the results for undersown FBCs for winter wheat recommendations because of the lack of statistical significance in the data and also because of the lack of any meaningful guidance from RB209 for likely fertility levels following undersown FBCs.

Table 6.3 Winter wheat N recommendations using the RB209 Measurement Method

Criteria for assessment	***Recommendations for winter wheat – West Field***				
	1*	***2*****	***3******	***4******	***5*******
Measured SMN (Feb)	*9.23*	*9.84*	*9.23*	*6.58*	*7.4*
Establish N levels already in crop (1000 shoots / m^2)	*22.5*	*22.5*	*22.5*	*22.5*	*22.5*
Allowances for net mineralisable N					
SOM technique (SOM level 5.3%)	*None*				
Incubation technique (Lober and Reeder, 1993) – Feb PMN data					
Non- undersown spring barley		*92.6*			
Mean of all direct sown FBCs			*119.04*		
Direct sown Peas				*89.1*	
Direct sown Phacelia					*164.3*
TOTAL “Net mineralisable N”	***31.73***	***124.94***	***150.77***	***118.18***	***194.2***
SNS Index by measurement method	***0***	***4***	***4***	***3***	***5***
N fertiliser recommendation for West Field (kg N ha^{-1})	***280***	***140***	***140***	***180***	***80***

*RB 209 SOM technique ** Incubation method using spring barley data

***Incubation method using mean straight sown FBC data

****Incubation method using straight sown pea data

*****Incubation method using straight sown *Phacelia* data

Allowances for the net mineralisable N using example FBCs have been calculated from the recommendations in RB209 in table 6.3. The SOM technique is an estimate of levels of N likely to mineralise from SOM over the forthcoming season. RB209 suggests that in mineral soils with under 10% organic matter negligible levels of mineral N will become plant available (recommendation 1). However, RB209 also states that a topsoil with organic matter of 10% may release 60-90kg N/ha^{-1} more N than a similar soil with 3% organic matter. This statement obviously introduces a major source of uncertainty into recommendations so generated. Recommendations 2-5 generated by the simple addition of PMN to the N levels already measured and estimated within the crops, demonstrate substantial variability and lack credibility.

The substantial diversity in the N fertiliser recommendations for winter wheat between field assessment and measurement methods demonstrates the limitations of these techniques. There is obviously an inability to take into account short term fertility building phases (recommendations 3, 4 and 5) without the use of PMN. The RB 209 scenarios make no provision for undersowing or for mulched incorporation as "green manuring". N inputs have the potential to have a profound effect on yield and environmental pollution, the diversity in these recommendations indicates the need for still greater precision and there should probably be a requirement for more rigorous assessment of soil levels prior to applications.

The soil incubation technique used in the trial described in chapter 4 (Lober and Reeder, 1993) provided accurate measurements of the PMN levels, but under optimal conditions. These are unlikely to occur in the field, so the mere addition of the PMN to the N already measured in the profile or within the crop seems too simplistic. A correction factor to mitigate the optimal condition simulated in the anaerobic incubation may be necessary to provide more field appropriate recommendations. Such a factor applied to PMN could be based on the likely C:N ratio of the residues or on the proportion of the N so assessed likely to be assimilated (and available for assimilation) into the winter wheat biomass at harvest (Table 6.4). Since this data was available from the West Field trial the amendments to the RB209 recommendations were calculated and are set out in table 6.4 and 6.5.

Table 6.4 Calculation of a PMN correction factor for RB209

FBC	Feb PMN kg N ha^{-1}	Winter Wheat at maturity (kg N ha^{-1})	Percentage N translated to biomass yield	Feb PMN transferred to biomass yield (kg N ha^{-1})	SMN Aug (kg N ha^{-1})	Total available for assimilation at harvest (kg N ha^{-1})
Non - undersown Barley	92.60	21.10	22.79	21.10	10.61	31.71
Fallow	91.70	26.83	29.26	26.83	24.20	51.03
Lupin	131.30	30.37	23.13	30.37	11.80	42.17
Crimson Clover	106.70	32.47	30.43	32.47	9.90	42.37
Black Medic	131.20	26.62	20.29	26.62	9.40	36.02
Vetch	154.50	28.67	18.56	28.67	9.30	37.97
Sweet Clover	91.30	26.58	29.11	26.58	10.30	36.88
Red Clover	139.70	31.55	22.58	31.55	21.70	53.25
White Clover	113.20	31.14	27.51	31.14	11.50	42.64
Mixture	96.40	33.90	35.17	33.90	12.70	46.60
Phacelia	164.30	24.22	14.74	24.22	8.60	32.82
Peas	89.10	28.53	32.02	28.53	11.50	40.03
FBC Mean	**119.04**	**28.50**	**25.71**	**29.76**	**12.81**	**41.98**

Table 6.5 Measurement method with correction factor.

Criteria for assessment	Recommendations												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Measured SMN (Feb)	9.23	9.84	9.86	9.14	11.96	10.04	9.49	6.79	10.31	8.34	11.55	7.4	6.58
Establish N levels already in crop (1000 shoots / m^2)	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5
Allowances for net mineralisable N from Table 6.4													
Non undersown spring barley	31.71												
Mean of direct sown FBCs		41.98											
Direct sown Fallow			51.03										
Direct sown Lupin				42.17									
Direct sown Crimson clover					42.37								
Direct sown Black medic						36.02							
Direct sown Vetch							37.97						
Direct sown Sweet clover								36.88					
Direct sown Red clover									53.25				
Direct sown White clover										42.64			
Direct sown Mixture											46.6		
Direct sown Phacelia												32.82	
Direct sown Peas													40.03
TOTAL “Net mineralisable N”	64	74	83	74	77	68	70	66	86	73	81	63	69
SNS Index	1	1	2	1	1	1	1	1	2	1	2	1	1
Wheat Fertiliser rec. (Kg N ha^{-1})	240	240	210	240	240	240	240	240	210	240	210	240	240

The recommendations set out in table 6.5 have removed much of the diversity shown in table 6.3, the straight sown fallow treatment, red clover and mixture apparently gave an SNS index of 2 and a recommendation of 210 kg N ha^{-1} for an 8-10t ha^{-1} target winter wheat crop. The recommendation used by the RAC farm staff was made on the basis of RB209 and previous cropping, West field in 2008 following spring beans, wheat received 200kg N ha^{-1} and a yield of 9.5t ha^{-1} was achieved.

6.4 Modelling using the FBC model (Cuttle et al., 2003)

The FBC model has a relatively simple structure, which makes it an attractive prospect for utilisation by agronomists and farmers. The modelling process offers the opportunity for commercial application of the data from this research; however, data for the FBCs which were most beneficial in the field trial are not currently represented in the model. Further model refinement is required to mimic more closely field conditions, e.g. actual rainfall figures, weed regeneration composition variability and growing crops accessing the entire SMN within the profile. A positive outcome for future modelling of short term fertility building phases is the knowledge of the key parameters, FW yields and below ground N contributions for improving the FBC model estimates.

6.5 Conduct of the field trial and pot experiment

The pot experiment suffered from slug and snails which required regular control with molluscicide applications and manual removal of the pests. The frame enclosure of the pot experiment protected the FBCs from pigeons and pheasants which were problematic in the field trial and required the use of agricultural fleece as a protectant on seedling peas and lupins and bird deterring devices which were distributed across the trial. The other main pest problem was rabbits which were deterred by a regularly maintained double ring electric fence. The damage from all of the above mentioned pests was maintained within a tolerable level and wasn't felt to have compromised the field trial and pot experiment.

The establishment of the FBCs in the autumn of 2007 was compromised by the rain at harvest and in particular the removal of the swathed spring barley straw, the failure of this sowing timing was attributed to this delay. Successful autumn establishment has been achieved in similar investigations in other northern European countries by Thorup – Kristensen *et al.,* (2003; 2012)The rain levels at harvest in 2008 of the test crops also compromised the quality of the grain, which displayed a high level of sprouted grains (13.4%) in quality analysis.

6.6 Additional discussion point

Authors such as Ladha *et al.,* (1988) and Jørgensen and Ledgard (1997) offer benchmark figures for FBC accumulation potential. Ladha *et al.,* (1988) suggest that N accumulation is 2.6kg N $ha^{-1}day^{-1}$, within this research the FBCs could not match these performance levels and over the 151day growth period N accumulation was in the range of 0.16 - 1.47 kg N $ha^{-1}day^{-1}$ (black medic - peas) (full results, appendix 3.2.1.6). Jørgensen and Ledgard (1997) suggested an correction factor for below ground accumulation, although leaf N fixation levels were not available within this research to test this correction factor.

Lignin content of residues would have been a useful addition to the biochemical information, and could perhaps have further aided interpretation of soil data. In addition the FBC model had the potential to be extended to use lignin information and the data from this research could have made an interesting refinement tool for the model. Another useful addition would have been a residue incubation trial within the laboratory to monitor residue N release. These additional dimensions were unfeasible due to time constraints and laboratory capacity.

Spring wheat test crops were not sampled throughout the test crop growing season, due to the difficulty of handling the quantities of samples which would have been generated. This could have provided more in depth understanding of the N release patterns of overwintered crop residues. Furthermore, the winter wheat crop sampling programme should have commenced at the point FBC residues of incorporation, perhaps with a more focused study at this point. This could have been a critical period in understanding residue behaviour.

Conclusions

- The aim of this research was to consider the attributes of a range of FBCs and to measure, as accurately as possible, their contributions as sources of N for subsequent cropping and their effects on subsequent crop yields. The null hypothesis, that FBCs have no influence on the accumulation of N and its recovery in the following season's cropping and have no effect on subsequent crop yields, has been disproved.

- The most effective FBCs for spring straight sowing were red and white clovers and the legume mixture.

- The most effective FBCs for undersowing in spring barley were black medic, red and white clovers and the legume mixture.

- Spring cropping was the most successful way to utilise the N accumulated by undersown FBCs probably because of the higher combined C:N ratio of the incorporsted material, which delayed the release pattern of N.

- PMN is a useful technique for planning fertiliser applications as it provides a useful indicator of likely future soil N levels.

- SMN provides information on N levels within the soil at sample time to act as a reference for immediate fertiliser recommendation.

- SMN and PMN together provide a more informed viewpoint of soil N status. Their combined use substantially improved the recommendations from the RB209 methods. However, the RB209 systems as presently constituted do not cater adequately for insertion of short term FBCs into an arable rotation.

- Autumn cropping of FBCs requires an early sowing window to ensure good establishment.

- Spring sowing provides more reliable and consistent FBC establishment.

- Undersowing gives an enhanced opportunity for cultural weed suppression.

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